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Russell

ELECTRIC LIGHT CABLES

AND THE

DISTRIBUTION OF ELECTRICITY.

THE SPECIALISTS' SERIES.

ELECTRIC LIGHT CABLES

AND THE

DISTRIBUTION OF ELECTRICITY.

BY

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PREFACE.

IN the early days of electric lighting, the distribution of the current did not present any very serious difficulties, since the lamps supplied by each dynamo machine were generally at no great distance from it; and it is therefore only recently, since the extension of central station lighting has forced them to the front, that the problems connected with the economical distribution of electricity have, as a general rule, attracted their fair share of attention. Although a considerable amount of experience has now been gained from the results of work already carried out, much still remains to be learnt, more especially concerning the durability of the materials employed to insulate the conductors; and it has been the author's aim, in preparing this work, to present to the reader such a description of the various systems of distribution and types of cable now in use, as will, he hopes, help forward the work that still remains to be done to perfect this branch of the *business of supply.*

For much of the descriptive matter, the author is indebted to the courtesy of the managers and engineers of various electrical companies, both at home and abroad, who have kindly supplied him with information concerning their work; and to them he is glad of this opportunity of tendering his cordial thanks.

November, 1891.

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ELECTRIC LIGHT CABLES

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CHAPTER I.

The Electric Circuit.—Conductors and Insulators.—Early Experiments in Electrical Transmission.—Ronalds' Underground Line.—First Telegraph Lines.—Lead-covered Wires.—Gutta Percha and India-rubber Insulation.—Overhead Lines.—Early Forms of Insulators.

In the last four or five years the problems connected with the economical generation and distribution of electric energy have attracted a considerable amount of attention; but the greater part of this has been directed to making improvements in the efficiency of the engines and dynamos, and in the methods of arranging and sub-dividing the plant into units; so that on the one hand each unit plant shall be small enough to permit of its always working at a fairly efficient load when in use; and on the other, shall not be so small as to lead to an inconvenient multiplication of the number of machines, with the attendant increase in the cost of labour.

Of equal, if not greater, importance is the distribution of the energy generated by the dynamos to the various places at which it is to be used, for the production of light, or motive power; or for any of the industrial processes in which its use has been found advantageous.

So long as the generating and receiving apparatus are comparatively close together, the distribution of electrical energy presents no great difficulties; but when extended areas are being supplied from central stations, the first cost of the distributing apparatus, and the annual cost of upkeep and of the energy wasted in it, together form such large items in the expenditure of any supply company, that it is necessary to study carefully all the problems connected with economic distribution.

The electric current is transmitted from one place to another by means of conductors, which must form a complete closed circuit; one portion of this circuit being in the generator, and another in the receiver, whilst the remainder forms a connecting link between the first and second. This last-mentioned portion of the conducting circuit is the distributing apparatus, and it should provide a path along which it is easy for the electricity to travel from the generator to the receiver and back again; and further, it should be so arranged that it is the only path along which the current can travel, or at any rate that no appreciable quantity of current can escape and complete its circuit back to the generator by a short cut without first passing through that part of the circuit which forms the receiving apparatus. Where several paths are available, the current will divide itself amongst them in inverse proportion to the resistances opposed to its passage, and it is therefore of the utmost importance that the resistance of the conducting circuit proper shall be very small compared with that of any other path by which the current can get back to the generator.

All known materials are to a greater or less degree conductors of electricity, and none are such perfect

conductors as to oppose no resistance to the current; yet, fortunately for the electrical engineer, there is a very marked difference in this respect between two classes of materials; one set offering a very small resistance as compared with the other, so small, indeed, that the name of conductor is applied only to materials of this class, whilst those of the second class, which offer a high resistance, are called insulators. By a suitable combination of conducting and insulating materials an electric circuit can be arranged so as to fulfil the conditions already named, one being just as necessary as the other, as without the conductor there could be no current of electricity, and without the insulator there would be no control over the path which this current should take. We see, therefore, that the problems of distribution may be divided into those connected with the conductor, and those connected with the methods of insulating it; and to these two sub-divisions may be added a third, in which the methods of fixing the insulated conductors and protecting them from mechanical injury must be considered.

For many years before the use of electricity as an agent for the production of light or motive power had become a commercial possibility, the electric circuit had claimed the attention of those engineers who were devoting themselves to the perfection of systems of telegraphy; and although the requirements of a telegraphic circuit differ in many important details from those of a lighting or power circuit, the work done by these pioneers of the electrical industry deserves careful attention; more especially since amongst the methods proposed and tried by them will be found some, which are almost identical with those in use by the electric-light engineer of the present day.

The earliest record of any attempt to transmit electricity to a distance dates back as far as 1727, when a Charterhouse pensioner, named Grey, erected a wire about 700 feet long, insulated by being suspended by silk threads, and observed the effect produced at one end of this wire when the other end was charged by applying to it an electrically excited glass rod. Twenty years later, Watson communicated shocks from a Leyden jar through an overhead line about two miles in length, the wire being supported on insulators of baked wood screwed to wooden poles, a method of insulating an overhead wire which was again tried in the early days of practical telegraphy.

The first instance of the use of a continuously insulated conductor was in 1812, when Baron Schilling successfully carried out the experiment of exploding an electrical mine, the current for which was conveyed to it by a conductor insulated with india-rubber and laid across the river Neva. Some four or five years later, Mr. Ronalds (afterwards Sir Francis Ronalds) carried out a series of experiments on a system of telegraphy at Hammersmith; when, in addition to a considerable length of overhead wire insulated by being suspended by silk threads from wooden frames, he also included in his circuit a length of rather more than 500 feet of underground wire. This wire was bare, and was threaded through thick g'ass tubes, the several lengths of which were butted together so as nearly to touch one another, and their ends enclosed in glass sleeves, which were slipped over the joints in the tube and fixed in place by means of a small quantity of soft wax. The glass tubes were laid in a wooden trough about two inches square, coated inside and outside with pitch, and filled up solid with the same material after the tubes were

in place. In a pamphlet entitled, "Description of an Electric Telegraph," and published in 1823, Mr. Ronalds described these experiments and the system of underground lines which he proposed to use, and on the advantages of which as compared with overhead lines he laid great stress, owing to their being less exposed to accidental damage; and it is interesting to see how completely at this early date he had elaborated an underground system, and had foreseen the necessity of making provision for easy access to the line, for testing and localizing faults, by dividing it into sections with test boxes placed at regular intervals, and by providing stations at which linesmen were placed, whose duty it was to look after the different sections of the line, and localize and repair any faults which might occur.

From the commencement, in 1837, of the era of practical electric telegraphy, inventors were very busy with the electric circuit, and in the forty years or so during which telegraphy was the only commercial application of electricity, innumerable patents were taken out for improvements in conducting circuits and the methods of insulating them. Iron wires coated with copper were proposed for the purpose of combining mechanical strength and electrical conductivity, as also were copper wires with silver cores and other compound wires in order to improve the conductivity; and the stranding of wires was introduced when considerable sectional area and flexibility were required. Many patents were issued for insulators of various shapes and materials, and for methods of suspending overhead wires, amongst these latter being one granted to Wheatstone in 1860 for supporting overhead cables in towns by links suspended from wires strained above them. In the matter of insulating

materials for making a continuous covering for the conductor, the Patent Record for this period shows that proposals were made at one time or another for the use of nearly every conceivable mixture of gums, resins, waxes and bituminous compounds, with one another and also with such substances as paper, fibrous materials, spun glass, powdered glass, sand, gypsum, etc., etc., and for enclosing these cables in lead tubes. Patents were also granted for insulating bare wires underground by threading them through glass or porcelain beads, by supporting them on insulators fixed in glazed earthenware troughs, and by laying them in troughs, fitted with glass or wooden distance pieces and filled in solid with asphalte, pitch, or cement.

Some of the proposals made during this period have been proved to be worthless; but others, although not successful when first tried, have formed the groundwork on which have been built up many of the systems now in use; the difference between success and failure being due to improvements in manufacture and greater care in handling and laying the conductors underground.

In the first patent taken out by Cooke and Wheatstone, in 1837, a plan for laying underground wires was described; and in the same year a five-wire line was laid between Euston Square and Camden Town, in which the wires were covered with cotton and steeped in a resinous compound, and were then laid in grooves cut in the top and sides of Λ-shaped baulks of timber which were laid in a trench in the ground. When the wires were in position, slips of wood were placed in the grooves to keep them in place, and the whole was covered with pitch before the trench was filled in. The insulation of these wires soon failed,

and in the following year, when a line was laid from Paddington to Slough, the baulks of timber were discarded and wires insulated in a similar manner were laid in iron pipes. This line had the same fate as its predecessor, and was replaced by one overhead, but the idea of using underground lines was not abandoned, and many experiments were made with cotton-covered wires saturated with resinous and tarry compounds, and laid in metal troughs or pipes, or in wooden troughs filled with asphalte, pitch, or similar material.

None of these lines lasted long, as the insulation was not damp proof, and the resinous compounds became decomposed; but in 1845 a great step was made in the right direction by the proposal to enclose the cotton-covered wires in lead tubes,—a proposal made first by Wheatstone and Cooke, who in May of that year took out a patent of which the following is a brief extract:—Separate copper wires are wrapped with worsted thread and varnished with shellac, and a number of these covered wires are then made into a bundle with whitelead and starch, and enclosed in a lead tube. The lead tube may be made of sheet lead wrapped round the wires and soldered along the joint, or it may be moulded round the wires by hydraulic pressure in the well-known manner of making lead tubes from semi-molten metal.

In August of the same year, Young and McNair took out a patent for lead-covered wires, their method being to cover the conductor with thread and coat it with asphalte, pitch, wax, and resin. The covered conductor was drawn through a vessel containing the hot compound, then through a nozzle which removed the superflous compound, and through a tube which passed through the cylinder containing the lead, and abutted

against a die through which the lead, at a temperature of from 250° to 400° Fahr., was forced by means of a hydraulic press. A third method was patented by Mapple, in 1846, in which the conductor was covered with cotton, soaked in tar or pitch, and passed into a lead pipe which was afterwards drawn down by being passed through rollers, or through a die, until it embraced the covered wire tightly. These three patents, dating back nearly fifty years, practically cover the whole ground so far as the lead casing is concerned, and describe in some detail the most approved methods which are in use at the present day; and the comparative want of success that attended the use of lead-covered wires in early telegraphic days must therefore be ascribed to the use of imperfect machinery, and to the incomplete expulsion of the moisture from the cotton covering, and subsequent impregnation of the latter with unsuitable compounds.

The first lead-covered wires appear to have been laid by the Electric Telegraph Company, in 1846, from the Strand to Nine Elms; the underground line consisting of a 3-inch cast-iron socket pipe containing two lead tubes covered with tarred yarn, in each of which there were four wires wrapped with two layers of cotton and filled in with a mixture of tar, resin and grease. The lead-covered cable was laid in lengths of about fifty yards; a sleeve of lead was slipped over the end of one length, the four conductors were then jointed, and the lead sleeve pulled down so as to cover the joint and soldered at each end to the two lengths of lead tubing. Other lines of a similar kind were laid, in which the wires were covered with cotton and drawn into a lead tube, in which there were slits made every six yards to facilitate the impregnation of the cotton covering. The

lead-covered wire was put into a cauldron containing a mixture of hot pitch, resin, and beeswax, and after remaining long enough for the mixture to get into the cotton covering, it was withdrawn, and the slits in the lead tube closed by soldering.

Cables covered with lead gave much better results than those which had previously been tried, but still their life was short, and whenever it was possible overhead lines were used in preference. About this time, however, a new insulating material was found in gutta percha; Faraday and Werner Siemens being credited with the discovery that it was a good dielectric; and in 1849 the first wires insulated with gutta percha were laid in London in cast-iron pipes. The wire was placed between two heated strips of gutta percha, which were made to adhere to it and to one another by the pressure of a pair of rollers between which they were passed. Wires covered in this way did not give satisfactory results, as the longitudinal joints between the two strips of gutta percha opened up and left the wire uninsulated; and it was not until a method was introduced by means of which the gutta percha was put on as a solid covering under pressure, that any measure of success attended the Telegraph Companies in their efforts to maintain an underground system. Even then failures were very numerous, and large sums of money were lost which had been spent on gutta-percha wires, and on laying them in conduits of iron pipe either solid or split, or of iron or wooden troughing, or of earthenware pipes.

India-rubber was also tried as an insulator, but with the methods of covering the wire which were then practised, it did not form a waterproof coating, and it decomposed too readily, so that its use never became very extensive; in fact, for telegraph work it may be

said that it was only used for indoor or overhead leading-in wires, for which purposes gutta percha was found altogether unsuitable. Although so many of these earlier lines failed and were replaced by overhead wires, there were some situations in which underground lines were a necessity; and engineers continued therefore to lay them, using for the most part gutta-percha wires, and getting better and better results as the manufacture was improved, and greater knowledge was obtained of the conditions under which the material would give the best account of itself. At the same time experience showed that the cast-iron socket pipe, with surface boxes placed at intervals of from 50 to 100 yards, was the best conduit; as it thoroughly protected the wires from mechanical injury, and allowed them to be drawn out and replaced when necessary. This form of conduit is now almost universally used for telegraph lines in England, and into it are drawn cables consisting of a number of wires insulated with gutta percha and protected by tarred tapes.

With regard to the overhead pole lines there is not much to be said, as after a short trial of insulators made of baked wood, every one settled down to the use of glass or glazed stoneware, and these are the materials most in use at the present time. The improvements that have been made in the shape and arrangement of the insulators, however, are considerable, as may be seen from the accompanying sketches of some of the shapes first employed.

Figure 1 shows the insulator used by Cooke, which was shaped somewhat like an egg with a hole through it from end to end, through which the wire passed, and which therefore afforded ample opportunities for surface leakage. The hour glass shape (Fig. 2) introduced by C. V. Walker reduced the leakage considerably, as the

wire was only in contact with the insulator at the centre, and there was therefore a greater length of surface over which the leakage current had to pass. Figure 3 shows the Bright cone, which, with modifications in the shape of the bell, is the form now generally

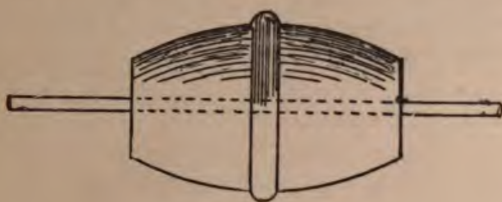

FIG. 1.

FIG. 2.

FIG. 3.

used, and which still further reduces the chance of leakage, since it only permits the current to escape in one direction instead of two, as is the case with the two other insulators.

CHAPTER II.

Conductors.—Relative Advantages of Different Materials.—Copper Wire.—Resistance.—Temperature Co-efficient.—Weight and Breaking Strain.—Economy of Working.—Sir William Thomson's Law.—Cost of Electrical Energy.—Load Factor.—Equivalent Current.—Calculation of Economical Current Density.—Professor Forbes' Tables.—Departures from Law of Economy.

When an electric current is flowing in any circuit, there is a continual expenditure of energy required to force it through against the resistance of the conductor, and this is accompanied by a fall of pressure along the line. This electrical energy is converted into heat energy, and so far as useful effect is concerned is absolutely wasted; so that it is desirable to reduce this expenditure of energy as much as possible, and not only is this so on account of the direct waste, but also because the rise of temperature of the conductor due to the heat generated by the current is itself harmful, causing an increase of resistance, and in some cases damaging the insulating covering, or even fusing the conductor; and further because the fall of pressure along the line cannot in most systems of distribution be allowed to exceed a certain small percentage of the pressure of supply, without giving rise to unsatisfactory results in the working of the receiving apparatus. For any given current, the waste of energy and the fall of pressure both vary directly with the resistance of the conductor; and this resistance varies with the material employed, and for the same material is proportional to the quotient of the length by the sectional area of the conductor.

The choice of a material is, however, influenced by

other considerations besides its specific resistance, such as the cost per unit weight of the material, and its specific gravity and breaking strain; since what is wanted is a conductor which, when insulated and erected in place, shall combine the smallest cost with the lowest resistance; and we shall see, when we come to the consideration of the insulation and erection of conductors, that the cost of these operations may be very materially affected by the relative values of the specific gravity and tensile strength of the metal or alloy which is used.

For the purpose of comparison, these data are given in the following table for various materials which have been used or proposed for use as electrical conductors.

TABLE I.

Material.	Conductivity. Pure Copper =100.	Specific Gravity.	Breaking Weight per Square Inch.	Wire with a resistance of 1 ohm per 1,000 yards at 32° Fahr.	
				Weight.	Diameter.
Soft Copper . . .	98	8·9	30,000	270	·173
Harddrawn Copper	97	8·9	64,000	273	·174
Galvanized Iron .	14	7·7	55,000	1632	·456
Cast Steel . . .	10·5	8·0	130,000	2260	·527
Aluminium . . .	55	2·6	26,000	140	·230
Silicon Bronze . .	97	8·9	64,000	273	·174
" " . .	80	8·9	76,000	330	·191
" " . .	45	8·9	110,000	587	·255

For continuously insulated conductors, the conductivity for equal sectional areas is the thing to be looked to; and if the conductor is so fixed that it is not subjected to tensile strain, soft copper is the best material; but if, for instance, the insulated conductor is to be suspended overhead without a bearer wire, so that

tensile strength is important, then hard-drawn copper or the best conducting quality of silicon bronze may be preferable. When a bare wire is suspended overhead, what is wanted is the greatest strength and conductivity for a given weight per unit of length; and if we take, as a coefficient for comparison, the product of the breaking weight and conductivity divided by the specific gravity, we find that hard-drawn copper, silicon bronze, and aluminium give the best results. The last named has been proposed as a suitable material on account of its lightness, as weight for weight it has nearly twice the conductivity of copper; but although the weight might be less, there would be no saving in the cost of poles, owing to the larger surface exposed to wind pressure. The second and third qualities of silicon bronze have the disadvantage of greater bulk and weight than either hard-drawn copper or the first quality of silicon bronze, and these latter are therefore the best materials to use. Iron or steel wire, although cheaper than copper, cannot compete with it, as their coefficients are respectively about one-seventh and one-fourth of that of copper, and their enormous weight and bulk would necessitate a greater expenditure on the supports.

In the early days of telegraphy copper wire was much dearer than at present, and could only be obtained with a conductivity of 30 to 40 per cent. of that of pure copper, and a breaking strain of about 30,000 pounds per square inch; and there were therefore great inducements to seek for a better material in the shape of compound wires, such as copper with a silver core to increase the conductivity, or with an iron core to increase the breaking strain. Owing to the great improvements which have been made of late years in commercial copper wire, such combinations are now of

no value; and, at the present time, copper has practically no rival which can compete with it as a conductor of electricity, and we shall therefore assume in what follows that the conductor is a copper wire of say 98 per cent. of the conductivity of pure copper. Since a rise of temperature increases the resistance of any conductor, we must correct for this as well as for the percentage conductivity of the wire, and for this purpose we must know the temperature coefficient, that is, the number by which the resistance of any wire at t° Fahr. must be multiplied to get its resistance at $(t+1)^\circ$. This coefficient is 1·0021, and the resistance of any wire at $(t+t')^\circ$ Fahr. may be found from the resistance at t° by multiplying the latter figure by $(1{\cdot}0021)^{t'}$.

Now the resistance at 32° Fahr. of a soft annealed wire of pure copper one foot long and one-thousandth of an inch in diameter is, according to Mattheisson's standard, 9·718 ohms; and if we assume an average working temperature of 80° Fahr., and a conductivity of 98 per cent., the resistance of a similar wire is equal to $9{\cdot}718 \times \frac{100}{98} \times (1{\cdot}0021)^{48}$ or 10·98 ohms. From this we can obtain a convenient general expression for the resistance in ohms of a copper wire in terms of its dimensions; for instance, $R = \frac{32{\cdot}9\,l}{10^6\,d^2} = \frac{25{\cdot}9\,l}{10^6\,a}$, where l is the length of the conductor in yards, d the diameter in inches, a the sectional area in square inches, and R the resistance in ohms at 80° Fahr. Similar expressions may be given for determining the weight and breaking strains, thus $W = 9{\cdot}09\,ld^2 = 11{\cdot}57\,la$, where W is the weight in pounds, and l, d, and a have the same meaning as before; and

B.W. $= 23500\,d^2 = 30000\,a$ for soft copper, and

B.W. $= 50000\,d^2 = 64000\,a$ for hard copper,

where B.W. is the breaking weight in lbs., and d and a are expressed as before in inches.

Having decided on copper as the material to be used, we can now proceed to consider the best proportions to be given to the conductor in order that it may fulfil the following conditions; viz., economy in working, moderate rise of temperature due to the current, and moderate fall of pressure. These three conditions cannot always be fulfilled simultaneously in all systems of distribution; and we therefore propose to consider each one separately, and then to see what is the best arrangement of conductors to suit all three under the various conditions of supply.

Economy of Working.

Since the energy wasted in heating any conductor is measured by the product of the current squared into the resistance, it is evident that it can be reduced indefinitely by reducing the value of the resistance; but, unfortunately, when the length of the conductor is fixed, its resistance can only be decreased by giving it a larger sectional area, and this increases its first cost. Now the annual charge on the conductor is made up of two items, the cost of the energy wasted in it, and the amount which must be put down for interest on capital expended and for depreciation; and the greatest economy is obtained when the sum of these items is as small as possible.

To fix our ideas, let us suppose that we have to transmit for 1,200 hours per annum a current of 100 amperes along a conductor whose length is 1,000 yards; that every Board of Trade unit of 1,000 watt hours that is wasted in the conductor increases our expenditure by twopence; and that a sum equal to 10 per cent. of the first cost of the line must be allowed for interest

and depreciation. Let us first try a conductor of 19/15, which is about as small as the heating of the conductor will allow, then the cost of the line may be £320, and the resistance ·327 ohms. The watts wasted will be 3,270, and the watt hours per annum 3,924,000, which at twopence per 1,000 watt hours gives £32 14*s.* If we add to this 10 per cent. on £320, or £32, we get a total annual cost of £64 14*s.* Now let us try a conductor of 19/13, costing £400 laid, and having a resistance of ·200 ohms. The watt hours per annum will be 2,400,000 costing £20, and interest and depreciation at 10 per cent. on £400 will be £40, giving a total annual cost of £60, or nearly £5 less than with the 19/15 conductor. Let us try a larger conductor still, say a 37/14 having a resistance of ·136 ohms, and costing £490 laid. The watt hours will be 1,632,000 and will cost £13 12*s.*, but the interest and depreciation will be £49, giving a total of £62 12*s.*, which is more than the cost with the 19/13 conductor. From this we see that there is some conductor between a 19/15 and a 37/14 which will give a minimum value to the annual cost, and the problem we have to solve is at what point does economy tell us to stop reducing the resistance; or, what is the same thing, increasing the area of the conductor; *i.e.*, at what point will the sum of the annual cost of wasted energy and the annual cost of interest and depreciation be a minimum.

Sir William Thomson first drew attention to this question in a paper on "The Economy of Metal Conductors of Electricity," read before the British Association in 1881, and showed that, if the capital outlay on the conductor varied in strict proportion to the weight of metal, then the most economical size of conductor was that for which the annual cost of interest and depreciation was equal to the annual cost of wasted energy.

The reasoning by which this result is arrived at is as follows: The annual cost of waste energy W is equal to the product of the square of the current C, the resistance R, the number of hours t per annum that the current is flowing, and the cost w of one watt hour; or $\mathrm{W} = C^2\,\mathrm{R}\,tw$, or since $\mathrm{R} = \frac{l}{a}$ multiplied by a constant $\mathrm{W} = C^2 \frac{l}{a}\,tw \times \mathrm{A}$ when $\mathrm{A} = \frac{\mathrm{R}\,a}{l}$. The capital outlay on the conductor K is equal to the weight of metal multiplied by a constant; and since the weight is proportional to la, we may write $\mathrm{K} = kla$, where k is a constant; and if p is the fraction of the capital outlay which is to be charged annually for interest and depreciation, we have $p\mathrm{K} = pkla$ as the annual expenditure on this account. The total annual expenditure is $p\ \mathrm{K} + \mathrm{W} = \left(pkal + \frac{C^2tw\mathrm{A}l}{a}\right)$ and this will be a minimum when $\frac{d(pkal)}{da} + \frac{d\left(\frac{C^2tw\mathrm{A}l}{a}\right)}{da} = 0$. This gives $pkl - \frac{C^2tw\mathrm{A}l}{a^2} = 0$ or $pkal = \frac{C^2tw\mathrm{A}l}{a}$; that is, the annual charge for interest and depreciation must equal the annual cost of wasted energy.

The actual relation between a and C is expressed by $a^2 = C^2 \frac{tw\mathrm{A}}{pk}$ or $a = C\sqrt{\frac{tw\mathrm{A}}{pk}}$; which shows that if the cost of a watt for all the working hours of the year and the rate of interest and depreciation are constant, then the economical conductor is always worked at the same current density. And since neither the length nor pressure appear in the equation, we see that the economical area is the same for all values of them.

In actual practice the problem of determining the most economical conductor is more complicated than the one worked out above, owing to the fact that the capital outlay on the conductors does not vary in exact proportion with the sectional area of the copper, and also on account of the difficulty of assigning a correct value to the annual cost of the wasted energy. As regards capital outlay, this is made up of the cost of the copper, of the insulation, of the supports or conduit, and of the labour of putting the conductor in place; and it is evident that all these items will not increase in cost in proportion to the area of the conductor. For example, with a continuously insulated cable laid in iron pipe under the footway, the cost of opening up a trench and making the pavement good again will be the same for very wide variations in the size of the conductor, the cost of the iron pipe does not increase nearly as fast as the area of the conductor, and the cost of the insulated cable, although more nearly proportional, is slightly less per unit area as the size increases. With bare conductors supported on insulators in a culvert, the cost of trenching and building the culvert remains practically the same for all conductors up to a joint area of several square inches; and with overhead lines the cost of the poles and insulators will not follow a proportional law, since the same poles would in each case be used for several sizes of conductor.

For each particular system of mains, however, it is possible to divide the cost into two parts without much inaccuracy, one of which will be a constant whilst the other increases in proportion to the area of the conductor; and we will therefore see what difference is made in the expression for the economical area when the capital outlay is equal to $l\ (ka + \mathrm{B})$ instead

of kla. The total annual expenditure will now be $p\,\mathrm{K} + \mathrm{W} = plka + pl\mathrm{B} + \frac{C^2 tw\mathrm{A}l}{a}$; and this will be a minimum, as before, when $\frac{dp\mathrm{K}}{da} + \frac{d\mathrm{W}}{da} = 0$; that is when $plk - \frac{C^2 tw\mathrm{A}l}{a^2} = 0$ since the differential coefficient of the constant $\frac{d.pl\mathrm{B}}{da} = 0$.

The best value of a is still given by the equation $a = C\sqrt{\frac{tw\mathrm{A}}{pk}}$, but k has not the same value as before, since it refers only to that part of the cost which is proportional to the area of the conductor. The law enunciated by Sir William Thomson will now be altered as follows:—The most economical size of conductor is that for which the annual cost of wasted energy is equal to the annual charge for interest and depreciation on that part of the capital outlay which is proportional to the area of the conductor.

To obtain the cost of wasted energy with any degree of accuracy, we must know the cost throughout the year of some unit such as the Board of Trade unit of one kilowatt hour, and the number of units wasted during the year in heating the conductor.

First, as to the cost of the unit, an important question at once arises as to what items of expenditure should be included in this cost for the present purpose. The total cost of a unit delivered to the customer is made up of the cost of fuel, water, oil, and petty stores, of labour and station supervision, of general management expenses, and of the annual charge for maintenance and depreciation on the whole plant. At first sight it may appear fair to include all these items, with the exception of that proportion of them which

belongs to the conductors themselves; but, on the other hand, it may be argued that the cost of material is really the only thing which will vary with the varying amount of waste energy in the conductors, and that the other charges will remain practically the same whether the output of the station is increased by two or three per cent. due to this waste or not. This question is a most important one, since the value of the result of the calculation depends on the accuracy with which the cost of the unit can be determined, and it will therefore be well to consider the reasons for adopting one method or the other.

In the design of a station, when the number of dynamo machines has been decided on, it is usual to make them of such capacity that they can together supply current for the maximum demand, plus an allowance for reserve, and that each can supply its current at such a pressure as will provide for the loss in the longest feeders which can be required in the district; and then to provide means of reducing that pressure as required by lowering the speed or adjusting the field strength. This being so, it is evident that so long as no mistake has been made in the estimate of the maximum pressure required at any station, the first cost of the dynamo machines is not affected by a variation in the amount of energy wasted in the conductors. In a similar manner engines and boilers are put in of equivalent capacity, and the building and fittings are arranged for the maximum output, and therefore the first cost of none of these items is affected in any way by the amount of wasted energy. The annual cost of station supervision and general management is practically independent of this variation in output, and so is the labour in the engine room, since it is only a question of running

the dynamos a volt or two higher or lower as the case may be. The depreciation on the actual generating plant may be slightly increased owing to its being worked at a greater output, and therefore it would appear to be right to make allowance for this, but it is very doubtful whether even this would be increased at anything like a proportional rate. When we consider that what we want to get is the actual increase of expenditure on account of the energy wasted in conductors, so that it may be balanced against the annual charge for interest and depreciation on them, it seems right in most cases to put on one side all the expenses connected with management, supervision, labour, and depreciation of buildings and fittings, and to include in the cost of the unit only the extra expenditure on fuel, water, oil, petty stores, and the depreciation on the generating plant.

The cost of these several items will vary very much with the conditions of supply and with local circumstances, and the engineer must therefore make a separate calculation for each particular case; the most important causes of the variation being the cost of the fuel and the load factor, or relation which the actual output of the plant bears to the maximum possible output, *i.e.*, the output which would be obtained if the plant were worked continuously at full load for the period under consideration. The name load factor was suggested for this ratio by Mr. Crompton in his paper on "The Cost of the Generation and Distribution of Electrical Energy," read before the Institution of Civil Engineers; and in this paper great stress was laid on the important part which the load factor plays in determining the cost, and much information was given in the shape of tables and diagrams which should be very useful to all those

engaged in the erecting or working of central station plants.

When the average cost throughout the year of a unit has been calculated, the next point to settle is the number of such units which will be wasted during the year in heating the conductor. In a constant current system the data required are simply the value of the constant current, and the number of hours in the year during which the plant is working; but in a constant pressure system, where the current is continually changing according to the varying requirements of the consumers at different times of the day and seasons of the year, it is necessary, so as to take into account these variations, to sum up the instantaneous values of the waste energy, and from them to calculate the value of a current which, if maintained continuously, would give the same waste. To do this requires a knowledge of the probable load curve, that is, the curve which shows the output of current at any time during the period under consideration; and although our knowledge on this point is as yet very imperfect, yet data are now being furnished by several stations, and we may fairly expect that at no very distant period sufficient experience will have been gained to enable the engineer to make a correct estimate of the probable curve for his district.

To calculate the value of the equivalent current from the load curve, we take a series of currents C_1, C_2, C_3 . . . . C_n, gradually increasing from zero up to the maximum, and for each current we find from the load curve the number of hours t_1, t_2, t_3 . . . . t_n in the year during which it is flowing; then the total waste is evidently represented by $R\ (C_1^2 t_1 + C_2^2 t_2 + C_3^2 t_3 + \ldots . + C_n^2 t_n)$, and since by definition this is to be equal to RC^2T, where C is the equivalent current

and $T = (t_1 + t_2 + t_3 + \ldots + t_n)$ = the total number of hours during which the plant is working, the value of C is given by the equation—

$$C = \sqrt{\frac{C_1^2 t_1 + C_2^2 t_2 + C_3^2 t_3 + \ldots + C_n^2 t_n}{t_1 + t_2 + t_3 + \ldots + t_n}}.$$

With regard to the question of the annual charge for interest and depreciation which has to be equated to the annual cost of waste energy, the former must entirely depend on the financial conditions of the supply company. The allowance for depreciation will depend on the type of conductor and the method in which it is supported overhead or laid underground, and at present it is not possible to assign accurate values to the depreciation for the various methods of line construction, since their employment is of such recent date that there are very few figures to work on.

The following examples will clearly show how the calculations should be made when the data are determined on, and may be taken as representing fair examples of two of the most important kinds of distribution with which one has to deal. (1) Suppose a main is to be laid in connection with a central station, and that it has been determined that the cost of each unit of 1,000 watts for one hour wasted in the conductors is 2*d.*, and that an examination of the load curves for a year at this or any other station, working under like conditions, has shown that the probable variation of output will be as follows:—The maximum current, say 200 amperes, will be required for 50 hours, 180 amperes for 100 hours, 160 amperes for 150 hours, 140 amperes for 150 hours, 120 amperes for 200 hours, 100 amperes for 200 hours, 80 amperes for 350 hours, 60 amperes for 500 hours, 40 amperes for 1,000 hours, 20 amperes for 3,000 hours, and 10 amperes for 3,060

hours. Let us further suppose that that part of the cost of the completed main which varies in proportion with the sectional area of the conductor is at the rate of twenty-two shillings per yard for one square inch section of copper, and that it has been settled that 10 per cent. shall be allowed for interest and depreciation. We can from these figures find the values of the several constants in the equation $a = C\sqrt{\frac{twA}{pk}}$ as follows:—

$$C = \sqrt{\frac{50\,(200)^2+100\,(180)^2+150\,(160)^2+150\,(140)^2+200\,(120)^2+200(100)^2+350(80)^2+500(60)^2+1000(40)^2+3000(20)^2+3060\,(10)^2}{50+100+150+150+200+200+350+500+1000+3000+3060}}$$

which gives—

$$C = \sqrt{\frac{24046000}{8760}} = 52{\cdot}4.$$

t = total hours working = 8,760.

w = at 2*d*. per 1,000 watt hours = ·002 pence.

A was made equal to $\frac{Ra}{l}$ but $R = \frac{25{\cdot}9\,l}{10^6 a}$

$\therefore A = 25{\cdot}9 \times 10^{-6}$.

$pk = 0{\cdot}1\,\frac{K}{la} = 2{\cdot}2$ shillings $= 26{\cdot}4$ pence.

Filling in these values in the equation gives—

$$a = 52{\cdot}4\sqrt{\frac{8760 \times {\cdot}002 \times 25{\cdot}9 \times 10^{-6}}{26{\cdot}4}} = 0{\cdot}217 \text{ square inches}$$

which gives for the maximum current a density of 920 amperes per square inch.

(2) Suppose a main is to be laid for a power supply where the load is constant at 200 amperes, and the plant is in use for 3,000 hours per annum. Since the load

factor is 100 per cent., and therefore the generating plant is working at its maximum efficiency, the cost of 1,000 watt hours should be somewhat smaller, and we will therefore take it as three half-pence instead of two-pence. Suppose the line to be a bare wire overhead, so that the portion of the cost that varies with the area of the conductor is practically the cost of the conductor itself, which we may take at the rate of ten shillings per yard per square inch of section, and let 10 per cent. again be allowed for interest and depreciation: we have the following values:—$C = 200$, $t = 3000$, $w = \cdot 0015$ pence. $A = 25\cdot 9 \times 10^{-6}$ and $p\,k =$ 12 pence. Putting in these values in our equation, we get—

$$a = 200\sqrt{\frac{3000 \times \cdot 0015 \times 25\cdot 9 \times 10^{-6}}{12}} = \cdot 622 \text{ square inches}$$

which gives a current density of only 320 amperes per square inch.

To save the labour of working out each separate case, Professor Forbes prepared some tables, which he published in 1885, in his Cantor Lectures on "The Distribution of Electricity." These tables are so arranged that they show the economical area of conductor per thousand amperes when the cost of laying an additional ton of copper (*i.e.*, that portion of the total cost which varies proportionately with the area of copper), the rate for interest and depreciation, and the annual cost of an electrical horse-power, are known. In Table II. each vertical column is headed by a possible cost of laying an additional ton of copper, and against each horizontal row is given a possible percentage rate to be allowed for interest and depreciation; the choice of the proper values having to be determined by the engineer in accordance with the con-

ditions of the case he is dealing with. In Table III. each horizontal row is appropriated to a possible annual cost of one electrical horse-power, and each vertical column is headed by a figure representing the area in square inches which should be used per thousand amperes. To explain the method of using these tables, it will be best to take an example: Suppose a current of 100 amperes is to be used, that the cost of laying an additional ton of copper is £200, that 10 per cent. is to be allowed for interest and depreciation, and that the electrical horse-power costs £20 per annum. Looking in Table II. along the horizontal row of figures opposite 10 per cent. until we come to the column headed £200, we find the figure 1·029. Turning now to Table III. we look along the horizontal row opposite £20 until we find the number most nearly equal to 1·029, in this case 1·018; the figure which heads this vertical column, namely 2·6, is the proper area of conductor for a

TABLE II.—*Cost of Laying one additicnal Ton of Copper.*

—		£60	£65	£70	£75	£80	£85	£90	£95	£100	£110	£120
Percentage allowed for interest and depreciation per annum.	5	·154	·167	·180	·193	·206	·219	·231	·244	·257	·283	·309
	7½	·231	·251	·270	·289	·309	·328	·347	·366	·386	·424	·463
	10	·308	·334	·360	·386	·411	·437	·462	·488	·514	·565	·617
	12½	·385	·418	·450	·482	·515	·546	·578	·610	·643	·707	·772
	15	·463	·501	·540	·578	·617	·656	·694	·733	·771	·849	·926
	20	·616	·668	·720	·771	·824	·875	·925	·976	1·029	1·131	1·235
	25	·771	·835	·900	·964	1·028	1·093	1·156	1·221	1·285	1·415	1·543

—		£130	£140	£150	£200	£250	£300	£350	£400	£450	£500
Percentage allowed for interest and depreciation per annum.	5	·334	·360	·385	·514	·643	·772	·900	1·029	1·157	1·286
	7½	·501	·540	·579	·771	·964	1·157	1·350	1·543	1·736	1·929
	10	·668	·720	·770	1·029	1·286	1·543	1·800	2·057	2·315	2·571
	12½	·835	·900	·964	1·285	1·607	1·929	2·250	2·572	2·893	3·205
	15	1·003	1·080	1·155	1·543	1·928	2·314	2·700	3·086	3·471	3·857
	20	1·336	1·440	1·540	2·056	2·571	3·089	3·600	4·115	4·629	5·144
	25	1·671	1·800	1·925	2·572	3·125	3·857	4·500	5·143	5·786	6·430

TABLE III.—*Section per Thousand Amperes in Inches.*

Annual Cost of Electrical Horse-power.	1	1·1	1·2	1·3	1·4	1·5	1·6	1·7	1·8	1·9	2
£											
5	1·628	1·356	1·147	·980	·857	·746	·658	·585	·523	·471	·426
6	1·954	1·627	1·377	1·176	1·028	·895	·790	·702	·628	·565	·511
7	2·279	1·898	1·606	1·372	1·199	1·044	·921	·819	·733	·660	·596
8	2·605	2·169	1·836	1·568	1·370	1·194	1·053	·936	·838	·754	·682
9	2·930	2·441	2·065	1·764	1·542	1·343	1·185	1·053	·942	·848	·767
10	3·256	2·712	2·295	1·960	1·713	1·492	1·316	1·170	1·047	·942	·852
11		2·983	2·524	2·156	1·885	1·641	1·448	1·287	1·152	1·037	·937
12			2·754	2·352	2·056	1·790	1·580	1·404	1·256	1·131	1·022
13				2·548	2·227	1·910	1·711	1·521	1·361	1·225	1·108
14					2·398	2·089	1·843	1·638	1·466	1·319	1·193
15						2·238	1·975	1·755	1·570	1·414	1·278
16							2·106	1·872	1·675	1·508	1·363
17								1·990	1·780	1·602	1·448
18									1·884	1·695	1·534
19										1·790	1·619
20											1·704

Annual Cost of Electrical Horse-power.	2·1	2·2	2·3	2·4	2·5	2·6	2·7	2·8	2·9	3·0	3·1	3·2
£												
5	·386	·355	·324	·298	·276	·255	·237	·221	·206	·192	·180	·170
6	·463	·426	·389	·358	·331	·305	·284	·265	·247	·230	·216	·203
7	·540	·498	·454	·417	·386	·356	·331	·309	·288	·269	·252	·237
8	·618	·569	·518	·477	·442	·407	·378	·353	·329	·307	·288	·271
9	·695	·640	·583	·536	·497	·458	·426	·397	·370	·346	·324	·305
10	·772	·711	·648	·596	·552	·509	·473	·441	·411	·384	·360	·339
11	·849	·782	·712	·655	·607	·560	·520	·485	·452	·422	·396	·373
12	·926	·853	·778	715	·602	·611	·568	·529	·493	·461	·432	·407
13	1·004	·924	·842	·775	·718	·662	·615	·573	·534	·499	·468	·440
14	1·081	·995	·907	·834	·773	·713	·662	·617	·575	·538	·504	·475
15	1·158	1·066	·972	·894	·828	·764	·710	·662	·617	·576	·540	·509
16	1·235	1·137	1·037	·954	·883	·814	·757	·706	·658	·614	·576	·542
17	1·312	1·208	1·102	1·013	·938	·865	·804	·750	·699	·653	·612	·576
18	1·390	1·279	1·166	1·073	·994	·916	·851	·794	·740	·691	·648	·610
19	1·467	1·351	1·231	1·132	1·049	·967	·899	·838	·781	·730	·684	·644
20	1·544	1·423	1·296	1·192	1·104	1·018	·946	·882	·882	·768	·720	·678

Annual Cost of Electrical Horse-power.	3·3	3·4	3·5	3·6	3·7	3·8	3·9	4	4·5	5·0	5·5	6·0
£												
5	·160	·150										
6	·192	·180	·170									
7	·224	·210	·199	·188								
8	·256	·240	·227	·215	·203							
9	·288	·270	·256	·242	·229	·217						
10	·320	·300	·284	·269	·254	·241	·229					
11	·352	·330	·312	·296	·279	·265	·252	·240				
12	·384	·360	·341	·323	·305	·289	·275	·262	·206			
13	·416	·390	·369	·350	·330	·313	·298	·283	·224	·181		
14	·448	·420	·398	·379	·356	·337	·321	·305	·241	·195	·162	
15	·480	·450	·426	·404	·381	·362	·344	·327	·258	·209	·174	·147
16	·512	·480	·454	·430	·406	·386	·366	·349	·275	·223	·186	·156
17	·544	·510	·483	·457	·432	·410	·389	·371	·292	·237	·199	·166
18	·576	·540	·511	·484	·457	·434	·412	·392	·310	·251	·209	·176
19	·608	·570	·540	·511	·483	·458	·435	·414	·327	·265	·220	·186
20	·640	·600	·568	·538	·508	·482	·458	·436	·344	·279	·232	·196

thousand amperes, and this gives an area of 0·26 square inches for 100 amperes. It must be remembered that the annual cost of an electrical horse-power is to be determined by multiplying its average cost per hour by the total number of hours in the year during which the plant is at work; and that the current for which the proper area is found is not necessarily the maximum current, but is what we have called the equivalent current; that is, the current which, if maintained constant during all the working hours, would waste the same amount of energy in the year as is wasted by the varying currents actually carried by the conductor.

The maximum annual cost of an electrical horse-power given in the table, viz., £20, is much lower than the actual cost which is likely to occur in any central station work where a continuous supply is maintained; but the tables may still be used by means of the following expedient. Suppose the cost per horse-power is n times any one of the figures given, then we proceed as before to find from Table II. the number, which is in the vertical column under the determined cost of laying one additional ton of copper, and in the same horizontal row as the percentage rate to be allowed. We then divide this number by n, and look along the horizontal row in Table III., opposite that figure which is equal to $\frac{1}{n}$th of our annual cost per horse-power, till we find the nearest number:—for example, suppose we again take £200 and 10 per cent. as the cost of laying the copper, and the rate for interest and depreciation; but that we take £54 as the annual cost of an electrical horse-power (this being about equal to a cost of 2*d*. per Board of Trade unit). We should again find the number 1·029 in Table II.,

and we may divide this by 3 and look opposite £18 per horse-power for the number 0·343. In this case we should find the nearest number was in the column headed 4·5 square inches, and by taking the proportional parts we should find that the most economical area per 1,000 amperes was about 4·3 square inches.

The question of the most economical size of conductor is a most important one, and all other considerations which may affect the area of copper to be used should be made subsidiary to it. It may not, however, be always possible to use the most economical size, since the heating effects of the current cannot be neglected; and where the load factor is very small, and consequently what we have called the equivalent current is only a small fraction of the maximum current, it will sometimes happen that the area dictated by economy is too small to carry the maximum current without an undue rise of temperature. For this reason, before finally determining what size of conductor is to be used, the heating effect of the current must be taken into account, and the laws which govern the rise of temperature of a conductor must therefore be considered. Under certain conditions of supply, the economical area of conductor, as given by the rules cited above, is not necessarily the best area to use in all cases; as, for instance, when the dynamos are all connected in parallel to common terminal bars and the pressure at the station end of all the mains is therefore the same; since with short mains the fall of pressure will be less than with longer ones, worked at the same current density, and it is therefore necessary to add resistance in the circuit of the shorter mains, so that the pressures at the lamps may be equalized. In such a case a smaller sectional

area of copper than that given by the equation may be used with advantage for the short mains, always supposing that the maximum current will not raise the temperature of the conductor above its safe limit.

CHAPTER III.

Effects of Rise of Temperature.—Mr. Kennelly's Experiments.—Insulated Conductors in Casing.—Copper Wire Tables.—Conductors Suspended Indoors.—Overhead Conductors.—Fall of Pressure.—Limiting Distance for each Pressure.—Effect of Increase of Pressure.—Feeders.—Alternating Currents.—Equivalent Current in Transformer Circuits.—Virtual Resistance of Conductors with Alternating Currents.

THE permissible rise of temperature in an electrical conductor is limited by three considerations, viz., that a rise of temperature increases the resistance of the conductor, and consequently the waste of energy; that it lowers the resistance of the insulating material with which the conductor is covered, and, if excessive, may permanently injure the insulating qualities of the covering; and that it may be the cause of fire if the conductor is in close proximity to combustible material. The increase of resistance of copper conductors, due to rise of temperature, is about one-fifth of one per cent. for each degree Fahrenheit; the exact relation between the resistances of the same conductor at temperatures of t° and $(t+t')^\circ$ Fahrenheit being expressed by the formula $R_{(t+t')} = R_t \times (1{\cdot}0021)^{t'}$; for instance, suppose the resistance of any conductor is 0·1 ohms at 60° Fahrenheit, it will be increased if the temperature is raised 50°, that is to 110° Fahrenheit, to $0{\cdot}1 \times (1{\cdot}0021)^{50} = 0{\cdot}11106$, or an increase of rather more than 11 per cent.; and with the same current flowing through it the waste of energy will be 11 per cent. greater at the higher temperature. The effect of a higher temperature on the insulating covering of a conductor varies very much according to the nature of the material used; but in all cases the insulation resistance is lower at the

higher temperature, and in some the insulating material is softened, which is a much more serious defect; since it allows the conductor to sink through the dielectric, permanently injuring the cable, and in time perhaps to work its way right through and make contact with the supports on which the cable is carried.

The rise of temperature of any conductor depends on the rate at which energy is expended in heating it, that is, on the product of the square of the current into the resistance; and on the facilities afforded for getting rid of the heat, which in turn depend on the amount of surface exposed, and on the disposition of the conductor with reference to its surroundings. It is evident that the rate at which heat is produced and the rate at which it is dissipated must be equal if the temperature is to remain constant. There are three ways in which the conductor may part with its heat, viz., by radiation, conduction, and convection; and the relative values of each of these for preventing a rise of temperature depend on the local conditions under which the conductor is operated.

Mr. A. E. Kennelly, in 1889, carried out a series of tests for the purpose of determining under practical conditions the laws which governed the relation between current, diameter, and rise of temperature; and as these tests are probably the most complete of any that have yet been made, a brief résumé of the results arrived at will be given. Tests were made on insulated conductors laid in wood casing, on bare copper wires indoors suspended in still air, and on bare and insulated wires suspended out of doors. Conductors in wood casing heated by a current are cooled by conduction through their insulating coverings, the casings, and walls of the room; and, when the outside of the casing has risen in temperature, by radiation and convection from its

surface. Under such conditions it was not likely that any simple law would be found to express the relation between current, diameter, and rise of temperature, and this proved to be the case; the results showing however, that the rise of temperature varies very nearly as the square of the current for any given wire; and that for a given rise of temperature, no serious error is made by assuming that the square of the current varies as the cube of the diameter of the wire. Mr. Kennelly published a table of safe currents for solid wires of various diameters, based on the rule proposed by the Committee of the Institution of Electrical Engineers, that "The conductivity and sectional area of any conductor should be so proportioned to the work it has to do that if double the current proposed be sent through it the temperature of such conductor shall not exceed 150° Fahrenheit." Assuming an average temperature of 75° Fahrenheit, this is equivalent to saying that the rise of temperature shall not exceed 75° with double the normal current; and the rule he gives to fulfil this condition is $d = {\cdot}0147\sqrt[3]{C^2}$, where d is the diameter of the conductor in inches, and C the current in amperes. The curves representing his experimental results are reproduced in Figure 4; and in Table IV., printed on pages 36 and 37, which gives the particulars of the various solid and stranded conductors in general use, the safe current for each in accordance with this rule is given, as also an approximate value of the current that would be required to raise the temperature 50° Fahrenheit.

The formula $d = {\cdot}0147\sqrt[3]{C^2}$ may also be written $C = 560\sqrt{d^3}$, and either may be used for calculating the proper relation between current and diameter for solid wires. When stranded conductors are used, it

must be remembered that their resistance is about 28 per cent. greater than that of a solid conductor of

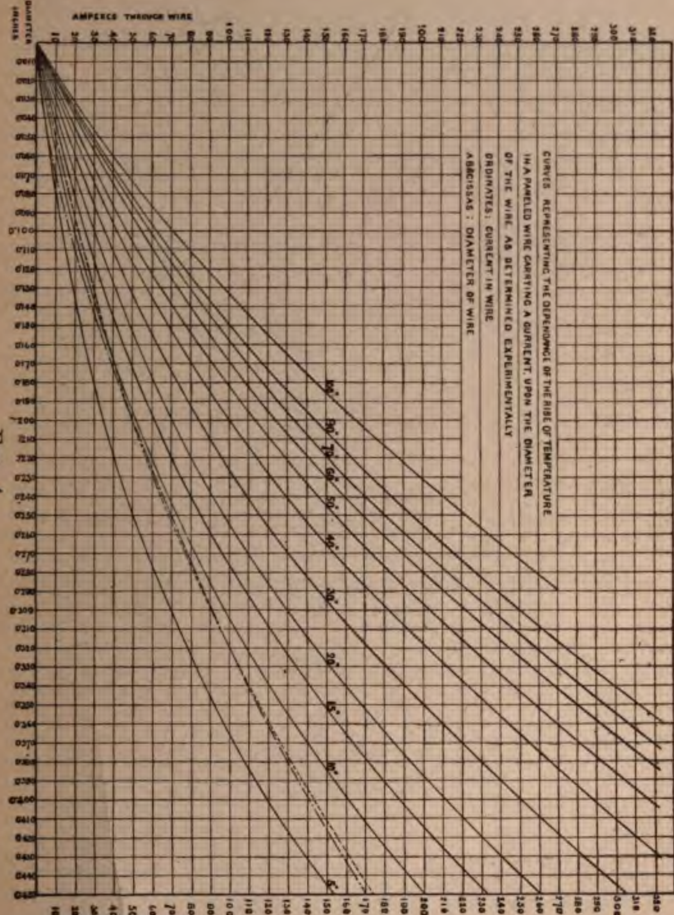

FIG. 4.

the same length and diameter, owing to the loss of space in stranding; and therefore the formula given

TABLE IV.

Legal Standard Gauge of Wire.	Diameter of Wire.		Area of Wire.		Weight of Copper.		Resistance at 80° Fahr. 98% conductivity.		Current which will raise temperature.				Volts lost per 1000 yards with current in column *
									Wire in Casing.		Wire Overhead.		
	Inches.	Millimetres.	Square Inches.	Square Millimetres.	lbs. per 1000 yards.	Kilograms per Kilometre	per 1000 yards.	per Kilometre.	18° Fahr. *	50° Fahr.	18° Fahr.	50° Fahr.	
18	·048	1·22	·0018	1·17	20·9	10·4	14·27	15·61	6	10	15	24	85
17	·056	1·42	·0025	1·59	28·5	14·1	10·49	11·47	7	12	18	29	73
16	·064	1·63	·0032	2·08	37·2	18·5	8·029	8·780	9	15	21	35	72
15	·072	1·83	·0041	2·63	47·1	23·4	6·344	6·938	11	18	25	40	70
14	·080	2·03	·0050	3·24	58·2	28·9	5·138	5·619	13	21	29	46	67
13	·092	2·34	·0066	4·29	77·0	38·2	3·885	4·249	16	26	35	56	62
12	·104	2·64	·0085	5·48	98·3	48·8	3·040	3·324	19	31	41	66	58
11	·116	2·95	·0106	6·82	122	60·7	2·444	2·673	22	36	47	77	54
10	·128	3·25	·0129	8·30	149	73·9	2·007	2·195	26	42	54	88	52
9	·144	3·66	·0163	10·5	188	93·5	1·586	1·734	31	50	64	103	49
8	·160	4·06	·0201	13·0	233	115	1·284	1·405	36	59	74	119	46
7	·176	4·47	·0243	15·7	282	140	1·062	1·161	41	68	85	137	44
6	·192	4·88	·0290	18·7	335	166	·8921	·9756	47	77	96	154	42
5	·212	5·38	·0353	22·8	409	203	·7317	·8002	55	90	110	178	40
4	·232	5·89	·0423	27·3	489	243	·6110	·6682	62	103	125	202	38
3	·252	6·40	·0499	32·2	577	286	·5178	·5663	71	116	141	227	37
2	·276	7·01	·0598	38·6	692	344	·4317	·4721	81	133	160	258	35
1	·300	7·62	·0707	45·6	818	406	·3654	·3996	92	151	180	291	34

TABLE IV.

No. of Wires in Strand.	Legal Standard Gauge of each Wire.	Diameter of Single Wire.		Diameter of Strand.		Equivalent Area of Strand		Weight of Copper.		Resistance at 80° Fahr. 98% conductivity.		Current which will raise temperature.				Volts lost per 1000 yards with current in col. *
												Wire in Casing.		Wire Overhead.		
		Inches.	Millimetres.	Inches.	Millimetres.	Square Inches.	Square Millimetres	lbs. per 1000 yds.	Kilograms per Kilometre.	per 1000 yards.	per Kilometre.	18° Fahr. *	50° Fahr.	18° Fahr.	50° Fahr.	
7	25	·020	·508	·060	1·52	·0022	1.42	25·6	12·7	11·58	12·66	7	12	17	28	81
7	23	·024	·609	·072	1·83	·0032	2·08	36·9	18·3	8·042	8·795	10	15	22	36	80
7	22	·028	·711	·084	2·13	·0044	2·85	50·6	25·1	5·908	6·461	12	19	27	44	71
7	21½	·030	·762	·090	2·29	·0050	3·24	58·0	28·8	5·147	5·628	14	22	30	48	71
7	20½	·033	·838	·099	2·51	·0061	3·92	70·5	35·0	4·253	4·651	16	25	34	55	68
7	20	·036	·914	·108	2·74	·0072	4·64	83·5	41·5	3·574	3·909	18	28	38	61	64
7	19	·040	1·02	·120	3·05	·0089	5·75	103	51·3	2·895	3·166	21	33	44	71	61
7	18	·048	1·22	·144	3·66	·0128	8·29	149	73·7	2·010	2·199	27	44	56	91	54
7	17	·056	1·42	·168	4·27	·0174	11·3	202	100	1·477	1·615	34	55	70	113	51
7	16	·064	1·63	·192	4·88	·0228	14·7	264	131	1·131	1·237	42	68	84	136	48
7	15	·072	1·83	·216	5·49	·0289	18·7	335	166	·8935	·9772	50	81	100	160	45
7	14	·080	2·03	·240	6·10	·0357	23·0	413	205	·7237	·7915	59	95	116	186	42
19	20	·036	·914	·180	4·57	·0197	12·7	228	113	1·308	1·430	38	61	77	124	50
19	19	·040	1·02	·200	5·08	·0243	15·7	282	140	1·059	1·158	45	72	89	144	47
19	18	·048	1·22	·240	6·10	·0351	22·7	406	201	·7355	·8044	59	95	116	186	43
19	17	·056	1·42	·280	7·11	·0479	30·9	553	274	·5404	·5909	74	120	144	232	40
19	16	·064	1·63	·320	8·13	·0624	40·2	722	358	·4187	·4525	90	146	175	281	37
19	15	·072	1·83	·360	9·14	·0790	51·0	914	453	·3269	·3575	108	174	207	333	35
19	14	·080	2·03	·400	10·2	·0975	62·8	1128	560	·2648	·2896	126	205	241	388	33
19	13	·092	2·34	·460	11·7	·129	83·2	1493	710	·2002	·2190	156	252	295	476	31
19	12	·104	2·64	·520	13·2	·165	106	1907	946	·1567	·1713	187	303	353	569	29
37	16	·064	1·63	·448	11·4	·122	78.6	1411	700	·2121	·2319	150	243	284	458	32
37	15	·072	1·83	·504	12·8	·154	99·6	1786	886	·1675	·1833	179	290	337	544	30
37	14	·080	2·03	·560	14·2	·191	123	2205	1094	·1357	·1484	210	339	394	634	28
37	13	·092	2·34	·644	16·4	·252	163	2916	1446	·1026	·1123	258	418	482	777	26
37	12	·104	2·64	·728	18·5	·322	208	3726	1848	·0803	·0878	311	503	578	932	25
61	13	·092	2·34	·828	21·0	·416	269	4816	2389	·0621	·0679	377	610	700	1126	23
61	12	·104	2·64	·936	23·8	·532	343	6154	3052	·0486	·0531	453	733	838	1350	22

above must be modified so as to take this into account. It is evident that the same amount of heat will be generated, whether a current C is passed through a resistance R, or a current $\frac{C}{\sqrt{1 \cdot 28}}$ is passed through a resistance $1 \cdot 28\,R$; and therefore for stranded wires the constant 560 must be divided by $\sqrt{1 \cdot 28}$, making the formula $C = 500\sqrt{d^3}$; and the constant ·0147 must be multiplied by $\sqrt[3]{1 \cdot 28}$, making the formula $d = \cdot 016\sqrt[3]{C^2}$.

Bare conductors suspended in still air indoors are cooled by radiation and convection. The amount of heat that is dissipated by radiation depends on the nature of the surface (a properly blackened copper wire radiating heat at about twice the rate of a bright one on the extent of surface exposed), and on the temperature difference. For the same wire, Mr. Kennelly found that the heat radiated per unit surface might be expressed by the equation $h = c \times \{(1 \cdot 0077)^t - 1\}$, where c is a constant and t is the temperature difference in degrees centigrade. The actual value of h in watts per square inch of surface, calculated from his figures for bright copper, is ·035 for a temperature difference of 18° Fahr., and ·104 for one of 50° Fahr. The total radiation from any bright copper wire is therefore $H_r = \cdot 035\,\pi dl = \cdot 110\,dl$ for 18° Fahr., and $H_r = \cdot 104\,\pi dl = \cdot 327\,dl$ for 50° Fahr., d and l being respectively the diameter and length of the wire in inches. A useful approximation, and one that will not lead to any serious error with any temperature rise that is allowed in practice, is that the heat radiated per linear yard of conductor $= \cdot 22dt$ where d is the diameter in inches, and t the temperature rise in degrees Fahr. In still air convection was found to be nearly proportional to the temperature rise, and to increase slightly with the diameter of the wire; but it appeared that for

ordinary practice it might be taken at ·00175 watts per linear centimetre per degree centigrade, which is equivalent to ·088 watts per linear yard per degree Fahrenheit, or $H_c = \cdot 088t$ watts. The sum of the radiation and convection $H_r + H_c$ must equal the heat produced C^2R, when the final temperature is reached; and since, assuming the air temperature to be 80° Fahrenheit, the resistance of one yard of any conductor can be expressed by $R = \frac{32 \cdot 9(1 \cdot 0021)^t}{10^6 \times d^2}$;

$$C^2 = \frac{10^6 \times d^2 t}{32 \cdot 9(1 \cdot 0021)^t}(\cdot 22d + \cdot 088)$$

or say $C = 80d\sqrt{\frac{t(d + \cdot 4)}{(1 \cdot 0021)^t}}$ for bright copper wires.

If the radiation from a blackened surface is taken as twice that from a bright one, then

$C = 80d\sqrt{\frac{t(2d + \cdot 4)}{(1 \cdot 0021)^t}}$ will give the current for a blackened copper wire.

When the wire, as is more generally the case, is suspended out of doors, the effect of convection is considerably increased, especially if any wind is blowing. In calm weather the results obtained by Mr. Kennelly showed that, to obtain the total emissivity of the wire, it was necessary to add a term to the value of the convection, which varied with the diameter of the wire; and that under these conditions the convection per linear centimetre and per degree centigrade was equal to $(\cdot 00175 + \cdot 013d)$ watts, which is equivalent to $(\cdot 088 + 1 \cdot 68d)$ watts per linear yard per degree Fahr., or $H_c = (\cdot 088 + 1 \cdot 68d)t$ watts, when d is the diameter in inches and t the temperature rise in degrees Fahr. This gives the total emissivity per yard for bright wires $H_r + H_c = (\cdot 088 + 1 \cdot 9d)t$, and equating this to C^2R, and assuming an air temperature of 60° Fahr., we get

$C^2 = \frac{10^6 \times d^2 t}{31{\cdot}5(1{\cdot}0021)^t}({\cdot}088 + 1{\cdot}9d)$, or $C = 246d\sqrt{\frac{t(d + {\cdot}046)}{(1{\cdot}0021)^t}}$.
If the wires are blackened, they will carry a rather larger current, but owing to the greater importance of convection the increase will probably not exceed five per cent., the equation for blackened wires being

$$C = 260d\sqrt{\frac{t(d + {\cdot}041)}{(1{\cdot}0021)^t}}.$$

From the equation for bright wires, the relation between current and diameter for temperature rises of 18° and 50° Fahr. has been calculated for the ordinary solid and stranded conductors, and the results are embodied in Table IV.; allowance being made for the stranding in the same way as before, which reduces the constants 246 and 260 to 217 and 230 respectively.

Fall of Pressure.—The third condition which must be fulfilled by the conductor has reference to the fall of pressure along it when a current is flowing. With some systems of distribution the fall of pressure is of no special moment; but when a number of lamps are being supplied in parallel circuit, it is of the utmost importance that the pressure at the lamp terminals shall not vary more than a certain percentage; and, since any variation of pressure at the lamps results in a still larger variation in illuminating power, this percentage must be a small one, certainly not exceeding 4 or 5 volts for a 100 volt lamp. The fall of pressure is measured by the product of the current into the resistance of the conductors leading from the dynamo to the lamp and back to the dynamo again; and this product CR must not be more than say 0·04 E, when E is the pressure of supply; but R varies as $\frac{l}{a}$ and since, when the size of the conductor

is settled by the law of economy, C varies as a, the product C R will be proportional to the length of the conductor; *i.e.*, to the distance between the dynamo and the lamp.

We therefore see that for each pressure of supply, when once the economical value of the ratio $\frac{C}{a}$ is settled, there is a definite maximum distance between the dynamo and the farthest lamp, which cannot be exceeded without a greater fall of pressure than is permissible; and further, that this distance is, other things being equal, proportional to the working pressure. For a working pressure of 100 volts this gives a permissible variation of 4 volts between the pressure at the lamp terminals with full current and that with one lamp only, and the maximum distance is given by the equation $L = 77a$, where L is the distance in yards from the dynamo to the farthest lamp, and a is the area in square inches which should be used for a maximum current of 1,000 amperes.

In isolated plants for the lighting of houses or ships, where a common practice is to work with a maximum current density of about 1,000 amperes per square inch, and when the distance from the dynamo to the farthest lamp is small, there is generally no difficulty in keeping well within the permissible limits of variation; but when the lamps are distributed over an extended area, as in the case of a central station supply, it is impossible to comply with this rule of variation of pressure on a simple 100 volt parallel system, without using conductors which are much larger than the economical size; and since economy is of the first importance, it is necessary to adopt special measures to bring the two conditions into line, by increasing the pressure of supply, or the number of points of

supply, or using a combination of both. An increase of pressure will be accompanied by a proportionate decrease in current for the same output in watts, but the economical area will also be decreased in proportion, so that the fall of pressure in volts per yard will be the same. Since, however, the number of volts variation which will give the same percentage fall is increased in proportion to the pressure, the distance from the dynamo to the lamps may be increased at the same rate; for example, suppose the economical current density to be 800 amperes per square inch, then the fall of pressure C R may be expressed by

$$C \times \frac{25{\cdot}9\,l}{10^6 \times a} = \frac{800 \times 25{\cdot}9\,l}{10^6} = {\cdot}0207\,l$$

when l is the length of the conductor in yards, or by ·0414 L when L is the distance from the dynamo to the lamps.

With this current density, $L = \frac{1}{{\cdot}0414} = 24$ yards per volt; and therefore if a 4 per cent. drop is permissible, the lamps may be 96 yards away on a 100 volt circuit, 192 yards on a 200 volt circuit, and so on. The use of high pressures is, however, not possible in a parallel system with the ordinary incandescent lamp, unless the conductors and other distributing apparatus are specially arranged to supply each lamp with a pressure not much exceeding 100 volts; and the extra first cost of, and the waste of energy in this auxiliary apparatus will always tend to reduce the advantages which accrue from increasing the pressure.

The second method of increasing the permissible distance between the dynamo and the lamps, without running counter to the laws of economy or variation of pressure, is that in which a number of distributing points are arranged at comparatively short distances

apart; these points being connected with the dynamo by feeder mains, and the pressure at the ends of these feeder mains or distributing points being maintained constant by regulating apparatus fixed in the station. Suppose that a 4 volt drop of pressure is allowable, and that we are working with a current density of 800 amperes per square inch; then the distributing points must be so arranged that no lamp is more than 96 yards distant from some one of them; but the distributing point itself may be, so far as variation of pressure is concerned, at a very much greater distance from the dynamo; the only condition being that the dynamo must be capable of supplying its current at a pressure equal to that required at the distributing point plus the fall of pressure in the feeder main.

The various methods by which current may be distributed over extended areas will be treated more fully under the heading of systems of distribution; but before leaving the subject of the proper proportioning of the sizes of conductors, some points connected with the distribution of alternating currents must be noticed, since these latter do not follow exactly the same laws as the direct current, and at times may require a special treatment if accurate results are to be obtained. First with regard to economical area; although, with energy at the same price and similar conductors, the same equivalent current may be carried, yet the maximum current may be less in an alternating current circuit containing apparatus like transformers or motors. This arises from the fact that the alternating current does not necessarily vary in direct proportion to the load; that is to say, that the output in watts is not measured by the product of average pressure into average current.

For example, when distribution is effected by means of open circuit transformers which require a large excit-

ing current (as much as 30 per cent. of the maximum current being required according to the figures given by Mr. Swinburne of his own transformer), the curve of output of current will be very different from that obtained with the same variation of load with the direct current; since with the alternating current it can never fall below 30 per cent. of the maximum, even at times when no lamps are being lighted. This must affect considerably the value of the equivalent current, when it is remembered that in many cases the output in watts during three-fourths of the time the plant is running is considerably below 30 per cent. of the maximum; indeed, in the example which was given on page 25, the equivalent current itself was only about 26 per cent. of the maximum. If we work out a case where the watts supplied to the transformers vary in the same way as they did in the example quoted, we should find that the equivalent current was about 37 per cent. of the maximum, instead of 26 per cent.; and that therefore, other things being equal, we should have to use a conductor having 40 per cent more area for the alternating current. With closed circuit transformers, the difference in current output is not nearly so great, since the exciting current may be only about 5 per cent. of the maximum, but in this case also the increase in the equivalent current should be taken into account.

Another matter, in which a conductor carrying an alternating current differs from one carrying a direct current, is the fall of pressure. This is due to an increase in the virtual resistance of the conductor, which varies with the rapidity of the alternations and with the diameter of the conductor, and was first pointed out by Sir William Thomson, who supplied figures for calculating its amount under various conditions. From

these figures Mr. Mordey has worked out a table, reproduced below, which shows the increase of virtual over ordinary resistance for various sizes of conductor at

TABLE V.

VIRTUAL RESISTANCE, ETC., OF CONDUCTORS WITH ALTERNATING CURRENTS.

Diameter.		Area.		Increase over Ordinary Resistance.	Current at 450 amperes per sq. in.	Watts at 2,000 volts.	Watts at 100 volts.	∾ per second.
MM.	Inches.	Sq. MM.	Sq. in.					
10	·3937	78·54	·122	less than $\frac{1}{100}$%	55	110000	5500	80
15	·5905	176·7	·274	2½%	133	266000	13300	
20	·7874	314·16	·487	8%	220	440000	22000	
25	·9842	490·8	·760	17½%				
40	1·575	1256	1·95	68%				
100	3·937	7854	12·17	3·8 times.				
1000	39·37	785400	1217	35 times.				
9	·3543	63·62	·098	less than $\frac{1}{100}$%	45	90000	4500	100
13·4	·5280	141·3	·218	2½%	98·5	197000	9850	
18	·7086	254·4	·394	8%	178	356000	17800	
22·4	·8826	394·0	·611	17½%				
7·75	·3013	47·2	·071	less than $\frac{1}{100}$%	32	64000	3200	133
11·61	·4570	106	·164	2½%	74	148000	7400	
15·5	·6102	189	·292	8%	131·4	263000	13140	
19·36	·7622	294	·456	17½%				

three different periodicities, and also the currents that may be carried by each at a current density of 450 amperes per square inch, and the corresponding output in watts at 2,000 and 100 volts.

From this table it will be seen that the effect only becomes appreciable with fairly large conductors, since 10 per cent. increase of resistance need not mean a fall of pressure of more than perhaps ½ per cent. of the

pressure of supply; and that therefore, for high pressures, there need be no difficulty in subdividing the circuits in such a manner as to avoid all trouble on this score. The inconvenience is, however, much greater with a low pressure distribution; since the limiting number of 16 candle-power lamps on a 100 volt circuit varies from 200 to 400, according to the periodicity; and although the difficulty may be got over by running a number of comparatively small circuits, this can only be done at the expense of a greater outlay in distributing mains. The cables may be run entirely separate from one another, or a number of lightly insulated conductors may be stranded up together into one cable, or the conductor may be made in the form of a tube or strip; the object in all cases being to so arrange the conductor that the distance from any point in its section to the nearest point on the surface shall not exceed, say, a quarter of an inch.

CHAPTER IV.

Systems of Distribution.—Series System.—Parallel System.—Feeders.—Combinations of Series and Parallel Systems.—Three-Wire System.—Accumulators as Equalizers.—Multiple Wire Systems.—Transformer Systems.—Motor-generators.—Accumulators.—Alternating Current Transformers.

THE choice of the system of distribution, which will be best suited to the requirements of any particular installation, is a matter which requires the most careful consideration; and although cases may occur where there is no question as to which system is most economical, yet in a general way this is not so; and we find that there are very great differences of opinion amongst engineers, and that a great deal may be said in favour of each of the rival systems that are in use at the present time. No matter what system is employed, the prime object of all must be the same, viz., to distribute the current from the terminals of the dynamo machines to the various places where it is to be used, for lighting or other purposes, with the smallest possible loss of energy and the smallest expenditure of capital: but in addition to this, there are other questions, such as convenience of regulation, and possible risks of breakdowns, which have to be considered; and the relative values assigned to these points, as factors in the determination of the choice of a system, vary very much.

If we consider only the conductor itself, we see at once that we can reduce the capital expenditure on, and the annual waste of energy in it by increasing the pressure; since with the same output an increased pressure allows of the use of a smaller current, which

can be carried by a smaller conductor, and at the same current density will cause less heating, and give a smaller percentage drop of pressure over any given length. This gain, however, is to a certain extent counterbalanced by the fact that the insulation of the conductor becomes more costly, and that in most cases the high pressures entail the use of special apparatus to reduce the pressure of supply before the current can be used by the consumer.

With few exceptions, the conditions of supply are such that either the pressure or the current must be maintained constant; for instance, when the current is to be used for lighting purposes, each individual lamp will require a definite pressure and current, and

FIG. 5.

the lamps may be so arranged that the same current shall flow through each, and that the pressure shall be varied according to the number of lamps in use; or, on the other hand, they may be connected up so that the pressure may be maintained constant and the current varied according to the number of lamps in use. The former is called the series system, and in it a conductor is led from one terminal of the dynamo to the first lamp, from it to the second lamp, and so on back to the other terminal of the dynamo, as shown in the accompanying Figure 5, where D is the dynamo machine and the circles represent the lamps; the

latter is called the parallel system (shown in Figure 6), and in it two conductors, each coupled to one terminal of the dynamo, are connected together by a number of branches in each of which may be placed a lamp.

At first sight it would appear that the series system must necessarily be the better of the two, since the pressure that can be used for lighting on the parallel system is limited by the maximum pressure for which an incandescent lamp can be made, and at present this is little more than 100 volts; whereas the pressure that can be used with the series system is only limited by difficulties of insulation in the dynamo

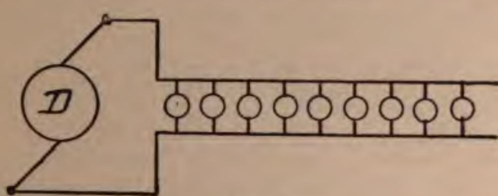

FIG. 6.

machine and, conductors, and in the case of direct current dynamos, by the difficulties of collecting the current. It is this last which really fixes the limit, but even with closed circuit dynamos the pressure may be as high as 1,500 to 2,000 volts; and with open circuit dynamos, such as are mostly used for arc lighting, it may be as high as 3,000 or 4,000 volts. It is evident that a great saving may be made in the weight of copper in the conductors by the use of such high pressures; and further, the series system has this great advantage, that the fall of pressure along the conductor does not in any way affect the illuminating power of the lamp, since this latter will burn at full power so long as the current is maintained constant.

The advantages of the series system of distribution are, therefore, that smaller conductors can be used, and that the distance from the nearest to the farthest lamp may be made very great without affecting the illuminating power. The disadvantages are, that the high pressure is carried all over the consumer's premises, and that therefore the dangers arising from an accidental contact with the conductors are increased; that the rupture of the circuit in any one place will stop the flow of current entirely, and that therefore special arrangements of a more or less complicated nature have to be made to prevent this happening when a lamp filament breaks, or an arc lamp does not feed properly; and lastly, that an absolute limit is put to the number of lamps that can be operated from one dynamo, by the fact that an incandescent lamp of the usual candle-power cannot at present be made to work with a lower pressure than about 6 volts. The conditions which are most favourable to the use of the series system are those which occur in street lighting, where the lamps are placed at regular intervals along the streets, and the distance of the farthest lamp from the dynamo and of each lamp from its neighbour is considerable. Under such conditions the use of the simple parallel system is practically impossible, since the weight of copper which would be necessary in the conductors, to keep the variation of pressure within fair working limits, is prohibitory.

With regard to the economy in conductors, one point should be noticed, which diminishes the advantages of the series system when employed for general distribution where the load varies much; and that is, that the waste of energy in the conductor is the same whether the full load or only 1 per cent of it is on; whereas in a parallel system the waste energy decreases even

more rapidly than the load. In calculating the economical size of conductor we must, therefore, for a series system take the full value of the current as the equivalent current, whilst in a parallel system, according to published data, the equivalent current is often only 20 to 25 per cent of the maximum; and from this it follows that, for the same area of conductor with equal annual waste of energy, the series system must, for similar conditions of supply, work with a pressure higher than that of the parallel system in the ratio of 100 to 20 or 25. On the other hand, however, the engines at the station will be working more economically at light loads than they would in a parallel system, since in a series system a reduction in load is accompanied by a reduction in speed of the generating plant, whilst the mean effective pressure in the cylinder and therefore the efficiency per stroke is maintained the same.

In the parallel system of distribution, the pressure should be kept constant at the terminals of all the lamps; and herein lies one of the greatest difficulties which have to be overcome in this system, because absolutely constant pressure can only be maintained when either no current is flowing or the conductors are of infinitely large area. Whenever a current is flowing through a conductor which offers some resistance to it, there is a fall of pressure, which, as has already been shown, varies in proportion to the current density and to the length of the conductor; and as the current density should be fixed by the economical law first propounded by Sir William Thomson, the fall of pressure may be said to depend only upon the length of the conductor. In practice a variation of pressure of about 4 or 5 per cent. at the lamp terminals is the maximum allowable; but, in a system of distribution from

a central station, only a part of this must be in the distributing conductors, since allowance has to be made for the housewiring, with the result that the maximum variation at the house terminals cannot exceed $2\frac{1}{2}$ to 3 per cent. The pressure of supply being limited to 100 volts, or thereabouts in the simple parallel system, on account of the difficulties of obtaining satisfactory incandescent lamps for higher pressures, this fall of $2\frac{1}{2}$ to 3 per cent. is numerically expressed in volts by the same figures; and therefore the greatest distance between the lamps nearest to and farthest from the dynamo must be small, unless conductors are used of much larger areas than those which are dictated by economy. The actual distances may be calculated from the equation $V = \frac{C}{a} \times \frac{25\cdot9 \times 2L}{10^6}$ where V = fall of pressure in volts, $\frac{C}{a}$ = the current density per square inch, and L = the distance in yards. If we take V as 3 volts, this may be written $L = \frac{10^6 \times 3}{51\cdot8} \div \frac{C}{a} = 57900 \div \frac{C}{a}$ which shows that, for a maximum current density of 1,000 amperes per square inch, the greatest distance between the lamps must not exceed 58 yards; at 800 amperes per square inch L becomes 72 yards; at 600 amperes per square inch 96 yards and so on.

The great disadvantage of the simple parallel system is then that the cost of the conductors practically becomes prohibitive when an extended area has to be dealt with; but, on the other hand, the requirements in the way of insulation are comparatively easy to fulfil, there is no chance of receiving dangerous shocks, and the arrangement of the conductors is extremely simple; so that this system is universally employed for all small installations, and has also been used to a great

extent for central station work, with the addition of feeding mains such as were mentioned in the last chapter. These feeding mains or feeders (Fig. 7) are conductors, by means of which a number of points like A or B in the district to be lighted are connected to the

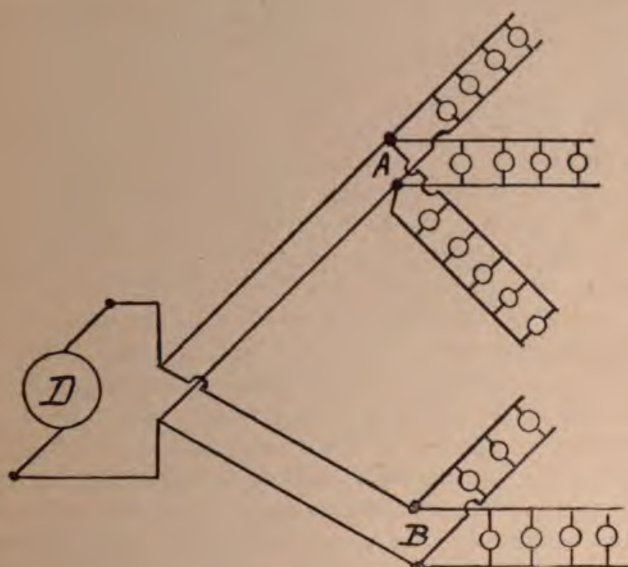

FIG. 7.

dynamos, and off which no branches are taken except at these points. Under these circumstances, each of these points may be considered as the centre of a supply, and as replacing a dynamo machine fixed at the end of the feeder, if arrangements are made for maintaining the pressure at each point at a constant value by varying it at the terminals of the dynamo machine.

The pressure at the distributing points may be measured by running back pressure wires from each of them to the station, so that an ordinary voltmeter in the latter place will register the pressure at the far end of the feeder; or by using a compensated voltmeter, that is, one so arranged that a coil carrying the main current, or a portion of it, acts in opposition to the voltmeter coil proper; this main current coil being so adjusted that it always balances the effect of the extra pressure due to the current flowing in the feeder, and so causes the instrument to register the pressure at the distributing point. In either case the reading of the voltmeter is kept constant by varying the pressure at the terminals of the dynamo, or by putting in or taking out resistances in the feeder circuit. It will be seen, therefore, that by a liberal use of feeders, the difficulties of variation of pressure at the lamps may be entirely got over; but, although the fall in the feeders need in no way affect the pressure at the lamps, the waste of energy which results from it, and the great size of the conductors in the simple parallel system, are both items of considerable importance in the cost; so much so indeed that it is difficult to understand why the two-wire parallel system should still be sometimes employed in preference to the three-wire system, which, as will shortly be seen, doubles the distance which can be covered at the expense of so little extra complication, that the two systems may really be compared on the same basis.

To reduce the outlay on the conductors and the waste of energy in them, several combinations of the series and parallel systems have been proposed and used; such as the running of groups of incandescent on a series circuit, the lamps in each group being llel; and the placing of two or more lamps in

series in each of the branches of a parallel system. The former system, represented diagramatically by Fig. 8, has been employed chiefly for the purpose of running incandescent lamps on a series arc lighting circuit; whilst the latter, which is shown in Fig. 9, has

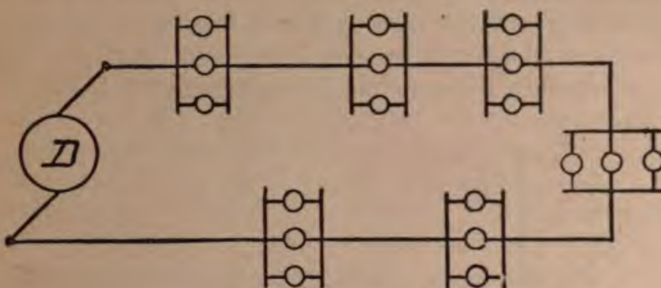

FIG. 8.

chiefly been used when lamps of small candle-power, which can only be made for pressures of say 25 to 30 volts, have been employed. In neither case are the individual lamps independent, but each group must be considered as though it were one lamp; and, for this

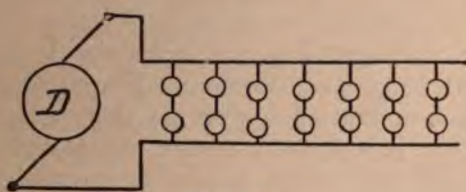

FIG. 9.

reason, neither of these combinations has had any very extended use, being decidedly unsuitable for the purposes of a public supply.

A modification of the second system, which was

first introduced by Edison in America, and by Hopkinson in England, has however met with general favour; since it combines the use of a higher pressure with all the advantages of easy manipulation which are found in the simple parallel system. This three-wire system differs from the one shown in Fig. 9 by having a third wire to which all the middle terminals of the lamps are connected, and by employing two separate dynamo machines connected in series

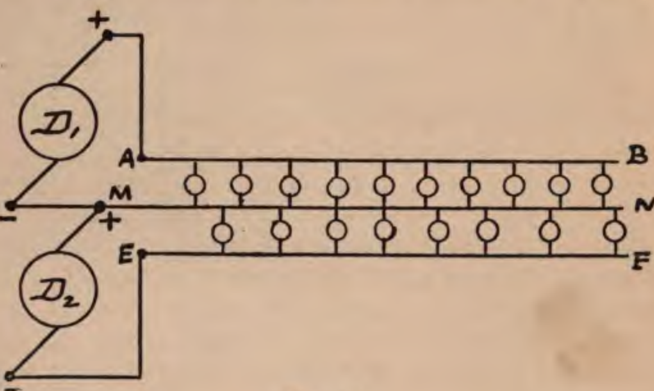

Fig. 10.

with one another. Fig. 10 shows the arrangement of the dynamos, conductors, and lamps; from which it will be seen that each dynamo may be considered to have an independent circuit completed by one of the outer conductors, the middle conductor, and the group of lamps connected to them. Taking the dynamo D_1, the current flows from it along the outer conductor towards B, through the lamps connected between AB and MN, and along the middle conductor to the negative terminal of the dynamo. The current from D_2 flows along the middle conductor

towards N, through the lamps between MN and EF, and along the outer conductor from F to the negative terminal of the dynamo. If the currents required for the two groups of lamps are equal, it is evident that no current can flow along MN; but that it will flow from the positive terminal of D_1 along AB, through the two sets of lamps, and will return along FE to the negative terminal of D_2. But if the currents are unequal, then a current of C_1 amperes will leave the positive terminal of D_1 and flow through the upper set of lamps to the middle conductor; there it will divide, a current of say C_2 amperes flowing through the lower set of lamps to the negative terminal of D_2, and a current of $C_1—C_2$ amperes flowing along the middle conductor to the negative terminal of D_1; that is to say, each dynamo will supply just the proper amount of current for its own group of lamps, the current in each outer conductor will be that required for the group of lamps connected to it, and the current in the middle conductor will vary in strength and direction according to the relative values of C_1 and C_2, being numerically equal to the difference of C_1 and C_2, and in the same direction as the smaller current of the two. In practice the difference in the values of C_1 and C_2 on a circuit supplying a large number of lamps is found not to be more at any time than half the maximum current, and generally it is much less, so that the area of the middle conductor need not be more than half that of either of the outside conductors.

With this system, since the pressure is doubled, the current required to supply the same number of lamps is only half that with the two-wire system; and therefore, at the same current density, the area of each outside conductor is one-half, and of the middle conductor one-quarter of the area of either conductor in the two-wire

system; giving, for equal lengths, a ratio of total weights of copper in the proportion of 5 : 8; for example, suppose 800 amperes requiring one square inch of copper is the current for the two-wire system, then the combined area of the conductors will be two square inches; whilst, in the three-wire system, the current will be 400 amperes, the area of each outside conductor one half square inch, and that of the middle conductor one quarter square inch, which gives one and a quarter square inches for the combined area. The fall of pressure per yard of conductor would be exactly the same in the two systems; but, since the working pressure in the three-wire is twice that in the two-wire system, the length of conductor which will give the same percentage fall is doubled, and the maximum distance between lamps for a 3 per cent. fall may, therefore, be increased to 116 yards for a current density of 1000 amperes per square inch, 144 yards for 800 amperes per square inch, 192 yards for 600 amperes per square inch, and so on. These distances are still much too short for the requirements of most districts, so that the use of feeders is equally necessary with the three-wire as with the two-wire system; but the distributing points may now be placed at twice the distance from one another, and the number of feeders may therefore be considerably decreased.

A modification of this system is sometimes employed, which dispenses with the third wire in the feeding mains, and permits of the use of one dynamo supplying current at 200 volts, instead of two dynamos each supplying current at 100 volts. Fig. 11 shows the arrangement of the apparatus in which D is the dynamo supplying current at 200 volts, which is conveyed by a two-wire feeder main to the distributing point A, at which is placed a battery of accumulators;

and to the two outside terminals and the middle terminal of this battery, the three distributing wires are connected. The accumulators here play the same part as their namesakes do in a system of hydraulic supply; the half battery connected to the circuit which requires most current discharges into that circuit, and so helps the dynamo machine; and the half battery, connected to the circuit in which the demand is smaller, is charged by the surplus current. Thus, suppose that the two circuits require currents of C_1 and C_2 amperes

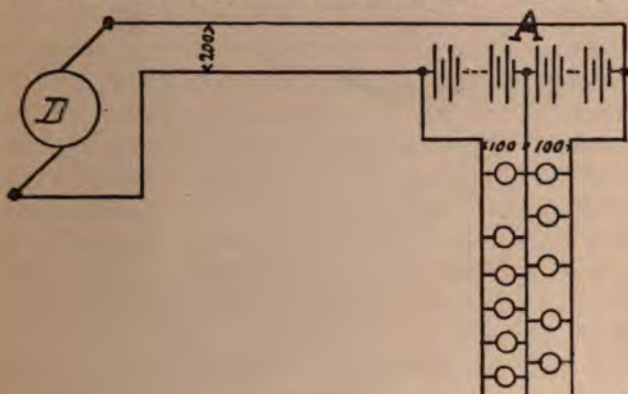

FIG. 11.

respectively, the dynamo will supply a current of about $\frac{C_1 + C_2}{2}$, and one-half battery will supply about $\frac{C_1 - C_2}{2}$ amperes, thereby making the total in the circuit $\frac{2C_1 + C_2 - C_2}{2} = C_1$ amperes; whilst the other half battery will be charged at the rate of $\frac{C_1 - C_2}{2}$ amperes, so that the current in the smaller circuit will be reduced to $\frac{C_1 + C_2 - (C_1 - C_2)}{2} = C_2$ amperes.

So far as first cost is concerned, there is no saving effected by this arrangement; since the cost of batteries at the distributing points more than counterbalances any saving due to there being no middle wire, and only one dynamo instead of two of half the output; but the batteries are able, during the hours of small demand, to supply all the current required without the aid of the dynamo machines, and consequently a saving in engine-room expenses may be made by stopping the running machinery altogether for some hours in each day. As a set-off against this, there is the cost of upkeep of the accumulators and their regulating gear, and of the loss of energy in the accumulators themselves, and this naturally depends on the merits of the particular type of accumulators employed. Mr. Crompton, who was the first to use this system in central station work, is a very strong advocate of its efficiency, and has employed it in several installations; but there are a good many engineers who still prefer to use the three-wire direct system without batteries, on account of the uncertainty as to the life of the plates and the cost of upkeep.

The multiple-wire system, of which the three-wire system is the simplest case, may be extended so as to permit of the use of still higher pressures; for instance, four wires may be used with a pressure equal to three times that at the lamp terminals, five wires with four times, and so on. The practical disadvantages of the extension of the system in this manner are, that it gives rise to greater complication in the arrangement of the mains and of the regulating apparatus, and that the introduction of the higher pressures into the consumer's premises is objectional. There are, however, one or two undertakings, in which five wires are employed for distribution with two-wire feeders, and pressure equalizers at the distributing points. The

pressure equalizers are in some cases accumulators, four 100 volt batteries being connected in series across the ends of the feeder, with five distributing wires connected one to each of the two outside and three intermediate terminals; whilst in others the pressure is equalized by means of electro-dynamic machinery.

This latter method has been adopted in some cases in

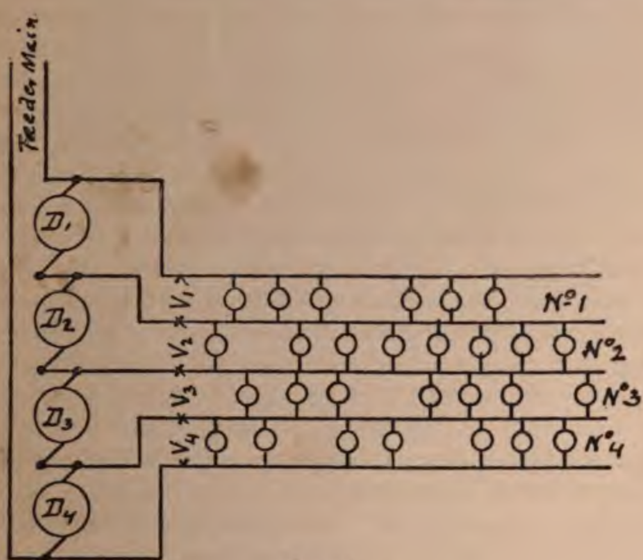

Fig. 12.

a system recently put down in Paris, the apparatus consisting of a quadruple dynamo machine, in which four armatures of very low resistance are mounted on one common shaft, and are connected together in series across the feeders. The two outside and three intermediate terminals of these armatures are connected one to each of the five distributing wires, as shown diagramatically

in Fig. 12 (in which, for the sake of convenience, the four armatures are shown side by side instead of in line with one another). Each armature runs in a magnetic field of the same strength and direction; each has the same number of turns of wire on it, and all are obliged to turn at the same speed, being mounted on one shaft; therefore the difference of potential between the feeders will be equally divided between the four armatures, so long as the resistance in the four lamp circuits, each of which is connected as a shunt on one of the armatures, is equal. Under these circumstances, a small current only flows through the armatures, just sufficient to keep them running at normal speed against the load due to the friction of the bearings, and the losses due to hysteresis and eddy currents in the armatures themselves. Suppose now that the number of lamps, and therefore the current, in circuit 1 is increased, and in circuit 2 is diminished; then, since the sum of the currents in each circuit and its corresponding armature must be the same for all of them, the current in number 1 armature must be diminished, and that in number 2 increased. The pressures V_1 and V_2 will tend to change in a similar manner, with the result that number 2 armature will tend to run faster, and number 1 to run slower. Since the two armatures are on the same shaft, and must therefore run at the same speed, number 2 will act as an electromotor, and give out power to drive number 1, which will become a generator and supply current. If the currents required in the lamp circuits are C_1, C_2, C_3, C_4, respectively, the current C supplied from the generating station will be equal to $\frac{C_1 + C_2 + C_3 + C_4}{4}$ plus a small amount which must be allowed for overcoming the losses in the regulator; and, if we suppose that C_1 and C_4 are

greater than C, and that C_2 and C_3 are less, then the armatures 2 and 3 will run as motors, and receive currents equal to $C - C_2$ and $C - C_3$ respectively; and the armatures 1 and 4 will run as generators, and supply current to their circuits equal to $C_1 - C$ and $C_4 - C$ respectively. The pressures V_2 and V_3 will be greater than V_1 or V_4 by an amount depending on the currents in the corresponding armatures and on their conductor resistances; but this variation of pressure may be rendered very small by making the resistance of the armatures small also.

Although there are a few instances of direct supply at pressures of about 400 volts, this system has not found much favour in England, owing to the fact that it is possible to get a shock from the full pressure by touching a part of a circuit inside a building, even although the insulation of that particular circuit is in excellent condition. This arises from the fact that the circuits in all the houses are connected together, and therefore, if a leak occurs in one house on an outside main, any one touching the wires in a house connected to the other outside main may complete a 400 volt circuit through his body. Even supposing that there is no actual fault in any one house, the general leakage on a circuit with a large number of lamps is sufficient to give an unpleasant shock; or the same result may be brought about, if two people in different houses touch the two wires at the same time. Although no serious results need be apprehended from a shock with this pressure under ordinary circumstances; the objections on this score, together with those arising from the extra complication of the system, have prevented it from being employed in England; and, whenever the pressure in the supply mains is greater than 200 volts or thereabouts, transforming apparatus is em-

ployed to reduce it to one suitable for the internal wiring of the building.

This transforming apparatus contains two circuits insulated from one another, one of which is connected to the primary or supply mains, and the other to the secondary or house mains. It is this insulation of the supply mains from the house mains that is one great advantage of the transformer system, since it divides the house circuits up into sets, each of which contains a comparatively small number of lamps, and can therefore be arranged so that its general leakage is very small; and further, it can be so arranged that the maximum pressure between any two points in the secondary circuits need never be more than 100 volts, and may be less if desirable.

The name of transformer, when used without further qualification, is generally applied to a modification of the induction coil, which is used with alternating currents; but motor-generators or accumulators may be used as transformers, when a continuous current is employed. The alternating current transformer consists of two coils of insulated wire interlinked with a magnetic circuit; one coil being connected to the supply mains is traversed by the alternating current generated by the dynamo machine; this alternating current produces reversals of magnetism in the magnetic circuit, which in turn induce an alternating current in the other coil which is connected to the secondary or lamp circuit. The motor-generator is a combination of two dynamo machines, one of which is supplied with current from the primary mains; and, acting as a motor, supplies the power necessary to drive the other, and cause it to generate a current of electricity. Two separate machines coupled together by mechanical gearing may be used for this purpose; but, in actual

practice, one machine with two separate windings on its armature is generally employed. When accumulators are used as transformers, two independent batteries are arranged in such a manner that one is in the primary circuit being charged, whilst the other is connected in the secondary circuit and discharges through the lamps; this separation of the primary and secondary circuits being what constitutes the difference between the transformer and the regulator.

The primary circuits of these transformers may be coupled up in series or in parallel with one another, and the lamps in the secondary circuit may also be connected in either of these ways; but of the four possible combinations, one presents such difficulties in the matter of regulation that, for all practical purposes, three only need be considered. These are :—

(1) Transformers in series, lamps in series.
(2) Transformers in series, lamps in parallel.
(3) Transformers in parallel, lamps in parallel.

(1) This system has been proposed by Mr. Bernstein as a means of overcoming some of the difficulties which occur in the direct series system, viz., that the number of lamps on each circuit and also the unit generating plant must be inconveniently small, and that the high pressure must be introduced into the house circuits. He proposes to use a continuous current, and to fix a motor-generator in each house to be lighted, their primary circuits being connected in series, and carrying a current of 50 amperes or more, whilst their secondary circuits each supply current, say at 10 amperes, to groups of lamps arranged in series as shown in Fig. 13. By this means, the size of the unit generating plant and the number of lamps on each circuit may be increased five times, or more, for the same maximum pressure, which does away with the incon-

venient multiplication of machines and circuits; but there is still the objection that, unless the output of the motor-generators is in all cases restricted to about 50 lamps of 16 candle-power, the pressure in the secondary or house circuit becomes higher than is convenient.

As regards the possible economy of the system, what

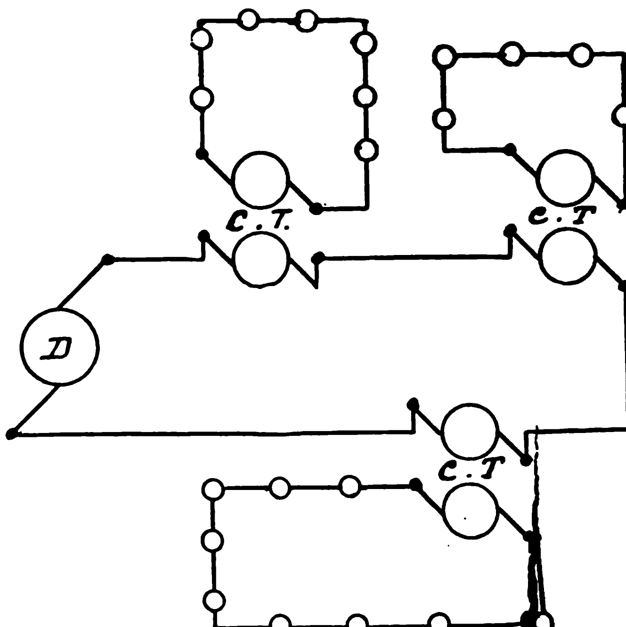

FIG. 13.

has been already said about the direct series system holds good; viz., that an increased economy may be obtained in the generation of the current, but that the system of distribution, with such load factors as are generally found, is uneconomical. If we consider the working conditions this will at once become evident;

since, in addition to the interest and depreciation on, and the cost of the energy wasted in the conductors, we have here, as in all transformer systems, to include the same annual charges for the motor-generators. Now each of these motor-generators must be able to supply current to all the lamps connected to it; whereas the maximum load on the circuit at any time may not exceed 60 per cent. of that required for all the lamps, and the average load may be only 20 per cent. of the maximum, or 12 per cent. of the added outputs of all the transformers. If we allow an electrical efficiency of 90 per cent. for each motor-generator at full load, which is probably too high for such small machines, and a loss of about 3 per cent. in the mains, we get a total loss in the circuit equal to about 12 per cent. of the maximum output of the transformers, without considering the losses due to friction or heating of the armature cores. Now this waste goes on all the same whatever number of lamps is in use; and therefore, on an average load of 12 per cent. of the transformer capacity, that is 20 per cent. of the maximum load of the whole circuit, we find that we have to generate at least two units at the station for each one used in the lamps.

A similar system may be used with alternating currents for working incandescent or arc lamps, and it has been adopted by the Westinghouse Co. in America, for both street and private lighting with arc lamps. The circuit is arranged as shown in Fig. 14, where D is the dynamo machine, and A.T., A.T., . . . are transformers serving one, two, or three arc lamps in series. By this system larger outputs may be got from one dynamo machine without excessively high pressures being used; since the current in the primary circuit may be greater, to any desired degree, than that required for the lapms.

The lamps themselves are insulated from the high pressure circuit, and can therefore be introduced into buildings without danger. Arc lamps of different candle-power requiring different currents, and incandescent lamps, could also be worked off the same circuit, by using transformers with different ratios between the primary and secondary windings.

(2) When the transformers are in series, and the lamps in the secondary circuit are in parallel, the

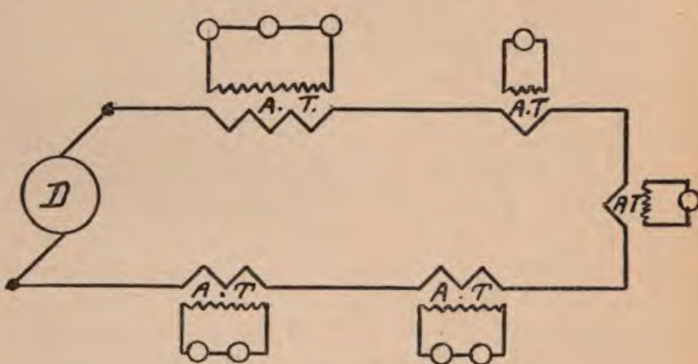

FIG. 14.

transforming apparatus generally takes the form of accumulators, of which there must be two independent sets, one in the charging or primary circuit, and one in the discharging or secondary circuit; these two sets being arranged in such a manner that they can, either by hand or automatically, be changed over from the primary circuit to the secondary, and *vice versâ*, according to their state of charge. This system has been worked out by the Chelsea Electricity Supply Co. in such a manner, that all changes of connections, and regulation of the accumulators, are performed auto-

matically at the distributing stations in which the batteries are grouped.

The general arrangement of the primary and secondary circuits is shown in Fig. 15, in which the generating plant is marked D, and the double sets of accumulators in each distributing station are marked

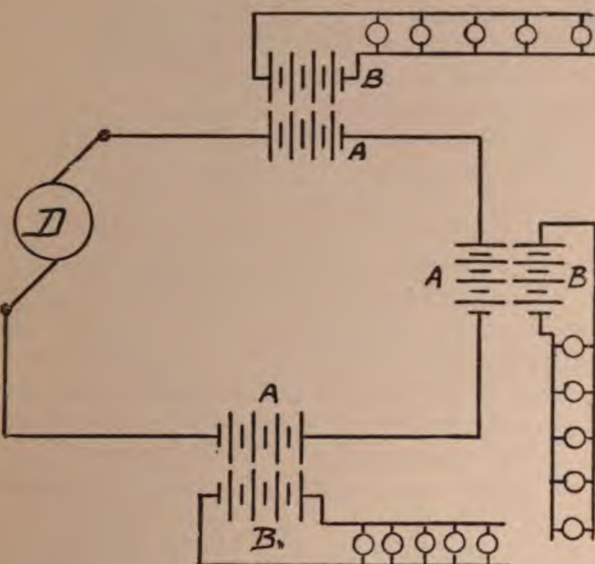

Fig. 15.

A B. The three sets A A A are shown connected in series in the primary circuit for charging, whilst the sets B B B are shown discharging into the secondary circuits, in which the lamps are connected in parallel. Automatic apparatus is provided at each station, which can transpose the two sets, connecting B in the primary circuit, and A in the secondary circuit, or can connect the two sets A and B in parallel in the

secondary circuit, at the same time disconnecting them from the primary mains, which are thus left free to be connected to motor-generators, which may be used to supplement the supply at the times of greatest load. The secondary distribution from each station is effected in exactly the same way as though each station contained its own generating plant, and may be arranged on the simple parallel, or the three wire-system, with or without feeders, as the conditions of supply make one or the other the more convenient.

The advantages claimed for this system are: that the distribution to the lamps is effected at low pressure from substations, to which the current can be supplied at high pressure; that the use of accumulators is a safeguard against the failure of the supply through any accident to the generating plant, and permits of the total stoppage of all running machinery during the hours of light load; that the arrangement of the transforming apparatus enables a greater maximum load to be supplied with the same generating plant, since this latter, exclusive of reserves, only has to charge one set of batteries at each station; whereas both sets may be coupled together, and their discharge supplemented by the current produced by the motor-generators at the time of greatest demand; and, finally, that the generating plant can always, when running, be worked at its most efficient load. On the other hand, the first cost of the accumulators is a very heavy item, and the annual charges for their upkeep, and for the electrical energy lost in them, must be set off against any increase of efficiency in the generating plant; so that it is probable that the advantages and disadvantages will nearly balance, and that whatever difference there is between the economy of this system and of others will depend on the life of the batteries, and this life

cannot be definitely settled without a much more extended experience of their use.

(3) When the transformers are arranged in parallel in the primary circuit, the alternating current transformer is universally employed; the distribution being carried out, either by means of a high pressure network of conductors with a transformer in each building requiring current, or by high pressure feeders supplying transformers in substations, from which the current for the lamps is distributed by a low pressure system of conductors. The first method, up till quite recently, has been the only one employed, as it is especially suitable for supplying districts where the lights are somewhat sparsely distributed over a large area; but it is probable that the second method will take its place to a great extent as the demand for the current increases. With a high pressure network, the difficulties of maintaining the insulation are increased by the necessarily large number of joints and connections in the distributing mains; and the energy wasted in the transformers is greater, when a separate one is fixed in each building, than it would be if a low pressure distribution from substations were employed; but against this must be set the fact that the sectional area of the distributing conductors will be much smaller, and the fall of pressure more easily kept within reasonable limits.

The arrangement of the circuit with a transformer in each house is shown in Fig. 16, where D is the alternating current dynamo, and A T are the transformers. When calculating the variation of pressure at the house terminals, the loss in the transformer must be taken into account; for instance, if the maximum fall of pressure between the dynamo and the house terminals is 3 per cent., 2 per cent. of this must

be allowed, as a general rule, for the transformer; leaving only 1 per cent. for the conductors, or 10 volts on a 1000 volt circuit, and 20 volts on a 2000 volt circuit. If the economical current density be taken, say, as 600 amperes per square inch, there will be a fall of pressure of 1 volt for each 32 yards of main; so that the maximum distance between the dynamo and the lamps is limited to 320 yards for a 1000 volt circuit, and

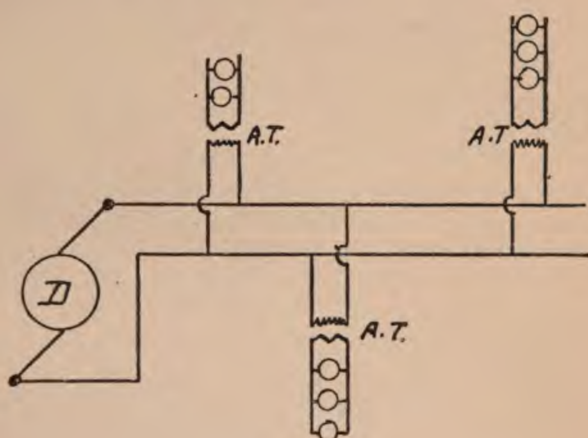

FIG. 16.

640 yards for a 2000 volt circuit, unless feeders are employed, and the pressure kept constant at their far ends.

When transformer stations are used, and the current distributed from them at low pressure on the simple parallel, or the three-wire system; the pressure is kep constant at the secondary terminals of the transformer and the high pressure conductors plus the transformers simply replace the feeder of the direct current system

(see Fig. 17). In this system, the distance between the transformer stations is regulated by the fall of pressure in the secondary distributing circuits, in just the same way as it is in a system with low pressure feeders, and the distributing mains are the same for both cases; so that, in comparing the relative economy of this with any low pressure system, we have only to decide

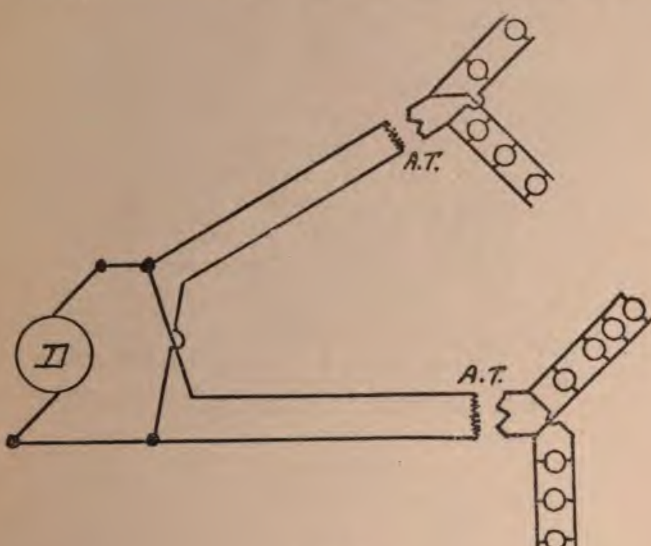

FIG. 17.

whether the cost of upkeep and of waste energy for the smaller feeders plus the transformers is more or less than the similar charges for the heavier conductors required on the low pressure system.

When very great distances separate the generating station from the lamps, a double transformation may be employed; that is, the current may be transmitted from the dynamo to substations in the district to be

lighted at extra high pressure, and from these it may be distributed either by means of a high pressure network with transformers in each house, or by high pressure feeders and low pressure distributing mains.

The economy of any of these transformer systems depends almost entirely on the efficiency of the transforming apparatus at varying loads; and this, though very high at full load, may be very small at the light loads which prevail during the greater part of the twenty-four hours. The efficiencies of alternating current transformers under varying loads have lately been the subject of much discussion, which it is to be hoped may result in further improvements in the design of such apparatus; and the relative economy of direct and transforming systems, which is dependent on this efficiency, has also attracted a good deal of attention. Although it is not possible to draw any hard and fast line, which shall define the conditions under which one or the other system is the more efficient, some calculations will be given in the following chapter, which may serve to give a general idea of their relative economy.

CHAPTER V.

Relative Economy of Direct and Transformer Systems.—Energy Wasted in Conductors.—Effect of Load Factor.—Energy Wasted in Transformers.—Cost of Mains.—Insulated Cables in Conduits.—Armoured Cables.—Bare Copper in Culverts. —Cables for High Pressures.—Cost of Transformers.—Calculations of Total Annual Cost of Distribution.

Of the various systems of distribution mentioned in the preceding chapter, those which have been most extensively used are the two- and three- wire low pressure direct systems, and the two-wire high pressure alternating transformer system. The suitability of any one of these systems depends on the local conditions of the district, such as the distance of the farthest lamp from the generating station, the probable number of lamps per yard of main, and the annual and daily load factors: and it is therefore impossible to say that one or the other system is the best in all cases, as for each district the claims of the several systems must be considered on their merits.

In many cases it is advantageous to place the station outside the district to be lighted, so as to obtain a cheaper site, or cheaper coal or water, or to avoid all chance of causing annoyance by noise, vibration, or smoke. Another point to be considered is the relative economy of one large station serving an extended area, with a number of smaller ones, each serving a portion of the district; and many engineers are of opinion that economy and convenience will lead to the establishment of large supply stations on the outskirts of the towns, where land is cheap, where fuel can be easily delivered and refuse got rid of, where there is a good supply of water which will allow of the use of condensing engines with their increased economy, and

where the expenses of engineering supervision and general management may be less than would be the case if there were several stations placed in different parts of the district to be lighted.

Up to the present time, the operations of the supply companies have not been on a sufficiently large scale to bring into prominence many of the disadvantages of operating large stations in the middle of a thickly populated district; but, if electric lighting is to make satisfactory progress, the probability is that the electricity works will follow the gas works, and that in future years they will be found outside, or on the outskirts of the district to be supplied. This removal of the station from a central position means either a great increase in the cost of mains or the use of high pressures, and this latter alternative necessitates the use of a transformer system, which lowers the efficiency of distribution, and has the disadvantage that at present the generating plant is more costly and less efficient than the plant required for the continuous current low pressure systems.

There is, however, a difference in the nature of the waste in the two systems, which to a large extent counterbalances the greater efficiency and cheapness of the low pressure plant; and that is, that in the latter case the greatest percentage loss takes place at the time of full load, whereas, with the transformer system, the efficiency increases as the load is increased. For an equal average waste, therefore, the ratio of maximum output at the station to maximum useful output is considerably higher in the direct system, when the mains are long; and the capacity of the plant must therefore be greater than that which is required for the same number of lamps on a transformer system. Taking this into account, it is probable that the cost

of the unit of electricity delivered at the terminals of the dynamo is practically the same for both systems; and, in comparing the economy of direct and transformer distribution under different conditions, we shall make this assumption, and take the cost of the unit of 1000 watt hours at twopence in all cases.

The waste energy, which has to be charged to the cost of distribution, is in the direct system entirely due to losses in the conductors; but in a transformer system, the losses in the transformers themselves form a very large percentage of the total waste. To calculate the losses in the conductors, we must know the way in which the demand for current varies at different times, and the ratio of the average demand to the maximum demand throughout the year; and we shall assume 17 per cent. as a figure which represents fairly the annual load factor in an ordinary town district; and further, that the load curves are of such a shape as the one of which particulars are given on page 24. There we found that the current, which would, if steadily maintained throughout the year, give the same total waste of energy in the conductors as the varying currents actually transmitted through them, was about 26 per cent. of the maximum current, and this would give a loss equal to about $\frac{1}{15}$th of that which would be caused by the maximum current flowing continuously. With the transformer system there will be an appreciable increase in the amount of energy wasted in the conductors during the 6000 or 7000 hours of very light load, due to the exciting current required by the transformers; and to allow for this we propose to increase the total loss in the conductors to $\frac{1}{13}$th of that which would be caused by the maximum current.

The value assigned to the load factor has a very important bearing on the relative economy of the two

systems of distribution; since with direct supply the whole loss is in the conductors, and any increase in the load factor, by making the equivalent current a greater percentage of the maximum, entails a greater waste in proportion to the square of this percentage; whereas, in the transformer system, only a part of the loss, and that a small one, is in the conductors; and therefore it is only this part of the total loss which is increased by the higher load factor. For example, suppose that five-sixths of the loss is in the iron transformer core, and one-sixth in the conductors, when the load factor is 20 per cent.; if the load factor is then increased to 40 per cent., the ratio of the losses under the latter conditions to those under the former is expressed by

$5 + 1\left(\frac{40}{20}\right)^2 : 6$ or $9 : 6$; whilst a similar increase in the average output with direct supply would make the losses four times as great.

The losses in the transformers depend, not only on the ratio of average to maximum load, but also in some cases on the ratio of the maximum number of lamps alight at any given time to the total number of lamps wired. This latter ratio must be taken into account, when a high pressure network with transformers for each house or pair of houses is employed; but it does not enter into the calculations, when the transformers are placed in substations from which the current is distributed by low pressure mains to the houses; and it is therefore necessary to consider these two cases separately. Suppose a house is wired for 50 lamps each of 60 watts, the transformer must be capable of supplying 3000 watts; although, except on very rare occasions, the maximum number of lamps alight at one time may be only 30, and the average load throughout the year may not exceed that due to 5 or 6 lamps. If we

assume that the ordinary maximum load is 60 per cent. of the lamps wired, and that the average is 17 per cent. of the maximum; we find that the 3000 watt transformer will have an average output of 306 watts, or about 10 per cent. of its maximum. The losses in such a transformer may be taken as equal to 3 per cent. of its maximum output for losses due to magnetization of the iron core, and say 2 per cent. for losses in the coils at full load; that is, there is a continual waste of 90 watts in the iron core; and, since the average output is only 10 per cent. of full load, the waste in the coils is about 2 watts. The average waste then is 92 watts, and the average output 306 watts; *i.e.*, the waste is at the rate of 300 watts for every 1000 watts supplied to the lamps.

If we now consider the second case, where the maximum load is equal to the full output of the transformer; and we take larger transformers, such as would be used at the distributing stations, giving say 2½ per cent. loss in the core, and 1½ per cent. in the coils; we shall find that the waste is at the rate of about 155 watts for every 1,000 watts supplied to the lamps.

The next point to be considered is the sectional area of the conductors, the cost of insulating and laying them, and the percentage of this cost which is to be allowed for interest and depreciation. The area of the conductors has to be considered both as regards economy and variation of pressure, the latter determining in many cases the area of the distributing mains, whilst the former consideration decides the area of feeders, and also that of distributing mains, when these latter do not exceed a certain length depending on the permissible variation of pressure and the economical current density. Before we can decide on the most economical current density, we must know the actual

cost of the mains in terms of the sectional area of the conductor, and we will therefore consider this matter first.

For low pressure mains, continuously insulated cable drawn into iron pipes or bitumen casing, armoured cables laid in the ground, or bare copper supported on insulators in a culvert, are most generally used; and, for each of these methods, the following estimated costs, which have been checked by comparison with the figures published from time to time, will, under ordinary conditions, be found fairly accurate. In each case the cost of the completed main may be expressed as $l(A+Ba)$, where l is the length in yards, a is the area of one conductor in square inches, and A and B are constants depending on the nature of the insulation and the system of laying. The value of A depends chiefly on the cost of opening up the ground and relaying the pavement, and on the cost of the pipe or conduit which is used for mechanical protection; while B is determined mainly by the quality and thickness of the insulating material.

The cost of an insulated cable does not, as a rule, vary in strict proportion to the area of the copper, the larger cables being relatively cheaper than the smaller ones; but within reasonable limits of variation of area, the departure from proportionality is not very great, and the reduction in price per square inch section of copper, as the area is increased, may be counterbalanced by the increased cost of the conduit, and of handling, laying, and jointing the cable, if the values of A and B are both determined for a medium size of conductor. From a comparison of the prices of different types of cable, it appears that, for such sizes as are mostly required in low pressure systems, the cost varies from twenty to twenty-six shillings per yard per square

inch of copper, the latter price being that at which a first-class rubber cable can be obtained, whilst the lower prices are mostly those of the fibrous and lead encased cables.

The cost of bitumen casing or iron pipes, including delivery on the ground and material for jointing, varies from fifteen to eighteen pence per yard per 2-inch way, and the cost of surface-boxes and of excavating and laying the conduit under the pavement, allowing, say, three shillings and sixpence per yard for vestry charges, is about six shillings and sixpence to seven shillings. A two-wire main may therefore be taken as costing, say, nine to ten shillings per yard, plus an amount obtained by multiplying the twenty to twenty-six shillings by twice the number of square inches of area in each conductor, or say, as an average figure, £$(\cdot 5 + 2\cdot 3a)$; and on the same lines a three-wire main, with the middle wire of half the area of either of the outside ones, may be taken at eleven shillings, plus twenty-three shillings multiplied by two and a half times the number of square inches in an outside conductor, or say about £$(\cdot 55 + 2\cdot 9a)$.

With armoured cables laid in the ground without the protection of a conduit, the cost of the latter is saved; but this is to some extent counterbalanced by the cost of the armouring. The cost of armouring does not vary exactly with the area, being proportionately more for small cables; and it may be taken as adding £$(\cdot 1a + \cdot 05)$ per yard to the cost of unarmoured cable. If we take the excavation and joint-boxes with vestry charges at £$\cdot 35$ per yard, and unarmoured cable at £$1\cdot 15a$ per yard as before, we get for the cost per yard of a two-wire main £$(\cdot 45 + 2\cdot 5a)$, and for that of a three-wire main £$(\cdot 45 + 3\cdot 125a)$.

The cost of the culvert for a bare copper system

varies somewhat according to the different designs, but an average figure is from eighteen to twenty shillings per yard for a concrete culvert, with surface boxes, insulators, etc., including an allowance for vestry charges at the same rate as before. The copper strip, delivered on the ground, straightened and fixed in place, may be taken at ten shillings per yard per square inch section; and we may therefore put the cost of a two-wire main at say £$(\cdot 9 + a)$ per yard, and of a three-wire main at £$(\cdot 95 + 1\cdot 25a)$ per yard. When this system is used, it is necessary in many places to put down insulated cables on account of the impossibility of finding space under the pavement for the bare wire culvert; and we propose, therefore, to take the average cost of a low pressure main at a figure based on about equal lengths of bare wire and insulated cable, say £$(\cdot 7 + 1\cdot 7a)$ for the two-wire, and £$(\cdot 75 + 2\cdot 1a)$ for the three-wire main.

For the high pressure distribution insulated cables must always be used; and it is important that the insulation should be of the best and most durable quality, and that the cables should be laid, on a drawing in and out system, in pipes which afford good mechanical protection. Owing to the comparatively small area of the conductors, their cost, even when allowance is made for the more expensive insulation, is a much smaller proportion of the total cost of the main than is the case in low pressure systems; and it is therefore economical to spend more in the first instance on the insulation, if a saving can be effected thereby in the cost of maintenance. The system, which is most extensively employed in England for high pressure underground wires, is that in which rubber cables are drawn into cast-iron pipes; and we shall take as our standard a 3-inch cast-iron pipe containing two cables, each of which

may be of any area up to about one-tenth of a square inch. When a larger area is required, which however is not often the case with such pressures as 2000 volts, a second pipe can be laid in the same trench, or a larger pipe than 3-inch diameter may be used. The cost of opening up the ground, laying the pipe, including surface boxes, drawing in the cable, and vestry charges, is about seven and sixpence per yard, and the cost of the cable itself varies from forty to fifty shillings per yard per square inch sectional area, according to the size of the conductor; and we may therefore take as an average figure £$(\cdot 375 + 4\cdot 5a)$ for a two-wire main.

The rate to be allowed for interest and depreciation will vary a good deal under different circumstances; and it affects the economy of the system in this way, that a low rate is favourable to the low pressure system in which the first cost of the mains is heavy, whilst a high rate is favourable to the high pressure system; but as a fair allowance we shall take 10 per cent. for all systems on the whole cost of the distributing plant.

We can now calculate the most economical current density in the conductors for each of the three systems by filling in the proper values in the equation

$a = \mathrm{C}\sqrt{\dfrac{t\,w\,\mathrm{A}}{pk}}$ or, what is the same thing

$$\frac{\mathrm{C}}{a} = \text{current density} = \sqrt{\frac{p}{t\,w\,\mathrm{A}}}\cdot\sqrt{k}.$$

The expression $\sqrt{\dfrac{p}{t\,w\,\mathrm{A}}}$ is a constant in which

$p = 0\cdot 1$

$$\left.\begin{array}{l} t = 8760 \text{ hours} \\ w = \cdot 002 \text{ pence} \end{array}\right\} t\,w = \text{annual cost of one watt} = £\cdot 073$$

$\mathrm{A} = \dfrac{\mathrm{R}\,a}{l}$ where R is the resistance of l yards of main,

that is of 2 l yards of conductor of an area of a square inches, and since the resistance of 2 l yards of conductor $= \frac{2l \times 25 \cdot 9.}{10^6 a}$

$$A = \frac{51 \cdot 8\, la}{10^6\, la} = \frac{51 \cdot 8.}{10^6}$$

Filling in these values of p, t, w, and A we get

$$\frac{C}{a} = 163 \sqrt{k}$$

k is that part of the cost of the main which varies directly with the sectional area of the conductor, and is therefore equal in each case to the constant by which a is multiplied. Substituting its values we get:—

For the two-wire direct system $\frac{C}{a} = 163 \sqrt{1 \cdot 7} = 212.$

For the three-wire direct system $\frac{C}{a} = 163 \sqrt{2 \cdot 1} = 236.$

For the transformer system $\frac{C}{a} = 163 \sqrt{4 \cdot 5} = 345.$

It must be remembered that these current densities are for what has been called the equivalent current, and that they must be divided by 0·26 for the direct systems, and by 0·28 for the transformer system, to get the densities with the maximum current; which are, therefore, in round numbers, 800, 900, and 1200 amperes per square inch respectively.

As regards the first cost of the distributing plant, we have still to fix on a price for the transformers themselves; and this we shall take at £6 per kilo-watt for the smaller transformers, each serving one or two houses; and at £5 per kilo-watt for the larger transformers placed in substations; these prices including fixing and accessories in both cases, and an allowance for the rent of a cellar, or the building of a transformer house or pit.

We have now all the data required to enable us to compare the annual costs of distribution on the several systems, and we will first consider an example which shows the importance of employing feeder mains, especially with the direct current systems. To avoid unnecessary complication, a small area, such as may conveniently be supplied from one feeder, will be taken; and the results thus obtained may, without appreciable error, be applied to larger areas by considering these latter as made up of a number of the small ones. Let us suppose that a maximum of 60,000 watts has to be

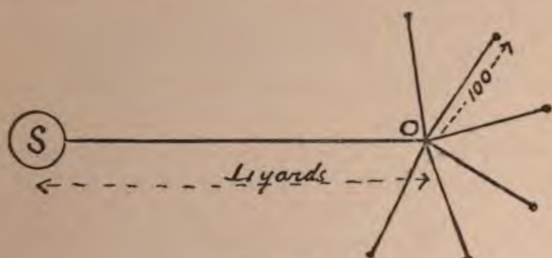

FIG. 18.

supplied to lamps grouped at the ends of six mains, each 100 yards long, and radiating from a point O, which is connected to the station by a main, L yards long, as shown in Fig. 18; that the maximum drop of pressure in the distributing mains is 3 per cent. for the direct systems; and, to allow for the drop in the transformer, say 1 per cent. in the transformer system.

The data we have to work on may be summarized as follows:—

Maximum load = 60,000 watts.

Average load = 10,000 watts.

Average waste in direct current mains = $\frac{1}{15}$ × waste due to maximum current.

Average waste in alternating current mains $=\frac{1}{13}\times$ waste due to maximum current.

Average waste in house transformers = 3,000 watts.

Average waste in substation transformers = 1,550 watts.

Cost of one watt per annum = £·073.

Cost of two-wire low pressure main per yard = £(·7 + 1·7a).

Cost of three-wire low pressure main per yard = £(·75 + 2·1a).

Cost of two-wire high pressure main per yard = £(·375 + 4·5a).

Cost of house transformers (100,000 watts capacity) = £600.

Cost of substation transformers (60,000 watts capacity = £300.

Rate for interest and depreciation = 10 per cent.

The economical current densities are 800, 900, and 1,200 amperes per square inch respectively, for the two-wire 100 volt, the three-wire 200 volt, and the two-wire 2,000 volt mains; and with these current densities, 72, 128, and 320 yards are the greatest lengths of distributing main that can be used without exceeding the permissible variation of pressure. When the distances are greater, the area of the conductor must be calculated from the formula $a=\frac{\cdot 000052\ (L+100)}{V_1}C$, where C is the current in the conductor and V_1 the permissible fall of pressure in volts.

Using this value of a and filling it in in the expression for the cost of the main, we get the following:

The two-wire 100 volt main costs

$$£\{420+\cdot 7L+\cdot 01768\ (L+100)^2\}.$$

The three-wire 200 volt main costs

$$£\{450+\cdot 75L+\cdot 00546\ (L+100)^2\}.$$

The two-wire 2,000 volt main costs

$$£\{225 + \cdot 375L + \cdot 000351\ (L + 100)^2\}.$$

Since at full load the waste of energy in the mains is 3 per cent. for direct current systems, and one per cent. for the transformer system, the average waste will be $\frac{\cdot 03 \times 60{,}000}{15} = 120$ watts for direct systems, costing £8 15*s.* per annum: and $\frac{\cdot 01 \times 60{,}000}{13} = 46$ watts for the alternating system, costing £3 7*s.* per annum.

When the lengths of the distributing mains are less than those mentioned above, viz., 72, 128, and 320 yards, the value of a must be taken at the economical current density, and the same rule applies to the calculation of the cost of feeders. For these latter we get the following expressions.

Two-wire 100 volts. Cost of feeders = £(1·975L). Average waste in feeders = 1·666L watts, costing £(·1216L) per annum.

Three-wire 200 volts. Cost of feeders = £(1·45L). Average waste = ·936L watts, costing £(·0683L) per annum.

Two-wire 2,000 volts. Cost of feeders = £(·4875L). Average waste = ·144L watts, costing £(·0105L) per annum.

When transformers are used £600 must be added for them to the cost of the mains, and £219 must be added to the annual cost of waste energy.

From these figures Table VI. has been drawn up, showing the total annual cost of distribution of each system with and without feeders (including £279 for interest and cost of energy wasted in transformers), for different distances between the station and the point O.

TABLE VI.

L in yards.	Two-wire 100 volts.		Three-wire 200 volts.		Two-wire 2000 volts.	
	Without feeders	With feeders	Without feeders	With feeders	Without feeders	With feeders.
	£	£	£	£	£	£
0	66	...	59	...	304	...
200	224	130	118	101	316	316
500	722	226	288	165	337	334
1000	2260	385	789	272	386	363
2000	7987	704	2611	485	535	422
3000	17251	1023	5256	699	619	482

The figures given above show the impossibility of economical working with either of the direct systems without feeders, when L exceeds 200 to 300 yards; and they also show that with the transformer system the difference in annual expenditure, with or without feeders, does not become important until L exceeds 1000 yards. As regards the relative economy of the three systems, it will be seen that the three-wire is always considerably cheaper than the two-wire direct system, and that both are cheaper for short distances than the transformer system. The cost of the latter, however, increases much less rapidly, and it will be found that it is equal to that of the 100 volt main with feeders when $L = 900$ yards, and to that of the 200 volt main when $L = 1600$ yards; but there is this most important difference between the direct and transformer systems, namely, that the loss in the feeders amounts to $37\frac{1}{2}$ volts in 900 yards of the 100 volt main, and to 75 volts in 1600 yards of the 200 volt main, or $37\frac{1}{2}$ per cent. in each case; whereas the loss in the feeders of the 2000 volt circuit is 56 volts for 900 yards, and 100 volts for 1600 yards, or 2·8 and 5 per cent. respectively

This means, that on the direct system the generating plant must have, say, 30 per cent. greater output than the alternating current plant, which will add very considerably to the first cost of the station, boilers, engines, and dynamos.

The other way in which a transformer may be used (that is when it is placed in a substation at the end of a high pressure feeder, and the current is distributed by low pressure mains to the various houses) reduces very considerably the amount of energy wasted; and for comparison Table VII. has been prepared, showing the annual expenditure on feeders only for a three-wire system, and on feeders and transformers for an alternating current system, the distributing mains in both cases being identically the same.

TABLE VII.

Length in yards.	Three-wire 200 volt feeder.	2000 volt feeder with transformer.
	£	£
200	42	155
500	106	173
1000	213	202
2000	416	261
3000	640	321

The length of feeder which gives the same annual expenditure in both cases is 930 yards, and the fall of pressure for this length is about 22 per cent. for the 200 volt and 2·9 per cent. for the 2000 volt main.

It will be remembered that the same rate for interest and depreciation has been allowed all through, the reason being, that the high pressure cable has been taken of such a quality as to make it proportionately as well able to stand the strains to which it will

be subjected as the low pressure cable; but even if on it the rate for depreciation is doubled, becoming, say, 10 per cent. instead of 5 per cent., the increase in the annual cost is very slight, amounting to only about £6 per 1000 yards run on the feeder.

The conclusions which may be drawn from the figures given in the two tables are, that in a general way it is economical to use a high pressure alternating current with transformers, whenever the average distance between the station and the lamps exceeds 1000 or 1200 yards; as beyond this distance the fall of pressure on the direct current mains at 200 volts or under becomes excessive, unless much heavier conductors are used than those which are dictated by economy. Under this distance there is a saving with the direct system, owing to the heavy expenditure for magnetizing the iron cores of the transformers, when these latter are connected on circuits running continuously day and night.

CHAPTER VI.

Various Forms of Conductors.—Stranded Conductors.—Tubular Conductors.—Conductors of Strip or Sheet.—Jointing.—Straight Joints.—T Joints.—Joints in Concentric Cables.

THE shape of the section of a conductor, and whether it is solid or built up of a number of wires stranded together, may affect for equal sectional areas the rise of temperature due to the passage of an electric current, the fall of pressure along the conductor, the cost of insulating it, and the ease with which it can be handled. Conductors are generally of circular section, since this shape is the most convenient for covering with the insulating material; but rectangular strips are sometimes used, where the sectional area is large and the conductor is carried on insulating supports placed at intervals, instead of being insulated with a continuous covering. The circular conductor may be a solid wire, or may be built up of a number of wires stranded together; or it may take a tubular form, consisting either of a drawn tube of copper or of a number of wires laid up over a circular core. The solid wire is generally the easiest and cheapest to manufacture, but for wires of large area it is too rigid; and where flexibility is required a stranded conductor is used by preference. In England the ordinary practice is to use no solid wire larger than a number 14 L.S.G. (·080 inch. diameter); and even for smaller sizes, the stranded conductor is often preferred; but in America and elsewhere the solid wire is frequently used for larger sizes, more especially for overhead work.

The natural strands are those in which the largest number of wires are added in each layer, which will fill up the space and maintain a circular section, and the total number of wires in any such stranded conductors may always be expressed by $3n\ (n+1)+1$ where n is any whole number; the diameter of such a conductor, consisting of $3n\,(n+1)+1$ wires each of diameter d, is given by the expression $(2n+1)d$; for example, if wires are to be laid up round a central wire of diameter d, it is evident that the circumference of the circle passing through all their centres will be $\pi\,(2d)$ or $6{\cdot}28d$; and this will allow of six wires being laid up, which with the central one will give a seven-strand conductor having a diameter of $3d$. If to this another layer of wires is added, the circumference of the circle on which their centres must lie will be $\pi\,(4d)$ or $12{\cdot}56d$; which will allow of twelve wires being added, making a nineteen-strand conductor with a diameter of $5d$. Each successive layer will add $2d$ to the diameter, and will add a number of wires to the conductor, which increases by increments of six, giving a series as follows: 7, 19, 37, 61, 91 . . . . for diameters of 3, 5, 7, 9, 11 . . . . times that of the single wire.

The weight per unit length of the stranded conductor is always more, by an amount equal to from $1\frac{1}{2}$ to $2\frac{1}{2}$ per cent., than the weight of an equal length of the single wire multiplied by the number of wires in the conductor; owing to the fact that the wires are laid up in a screw thread path, so that each wire once in the lay completely encircles the strand to which it is being added; and in practice it is found that the resistance of a stranded conductor is always less than that of an equal length of the single wire divided by the number of wires in the conductor, and this by a percentage which is nearly equal to that named

above as giving the increase of weight. If this correction is allowed for, and the resistance of the strand compared with that of a solid conductor of the same diameter, it will be found that the former is from 27 to 30 per cent. greater than the latter, a fair average figure for the strands most generally used being about 28 per cent.; and if the diameters of a strand and a solid conductor having the same resistance are compared, it will be found that the former is from 12½ to 14 per cent. more than the latter.

This increase of diameter over that of a solid wire of the same resistance will allow of a slightly larger current being carried for the same temperature rise; but it unfortunately affects also a much more important matter, viz., the cost of insulation, by adding nearly 30 per cent. on to the weight of insulating material that would be required to give the same resistance with a solid wire. With a view to overcoming this objection, a conductor built of segmentally shaped wires, which would fit close together and fill up the space left unoccupied by round wires, was proposed for one of the early submarine cables; but the diminished flexibility and the increased difficulties of laying up such wires prevented this form of conductor from ever being adopted.

When very great flexibility is required, the conductor may be composed of a number of strands each of which is itself a stranded conductor; or a number of very small wires, as many as 300 being sometimes used, may be twisted together at the same time, instead of being stranded up layer after layer in the usual manner.

The tubular form of conductor is sometimes used with alternating currents, because a large sectional area can then be employed with a smaller increase of virtual resistance than would occur with a solid wire;

but its chief use is as the outer conductor of a concentric cable, that is a cable which contains both the out and return conductors, the outer one taking the form of a tube which entirely encloses the inner conductor and its insulating covering. The advantages of placing the two conductors concentrically are, that with alternating or unsteady currents, the inductive action of one conductor on neighbouring wires is neutralized by that of the other conductor; and that with any current the system of conductors can be so arranged that the inner conductor cannot be touched, and cannot make any contact with earth, without first making a contact with the outer conductor.

The first point is of considerable importance where the conductors pass very close to the wires of telephone circuits; but, under ordinary circumstances, no serious interference with the working of the telephones is caused by two separate well insulated conductors lying close side by side in the same pipe; and it is therefore very doubtful whether, for this reason alone, the advantage gained by the use of the concentric cable is sufficient to counterbalance the greater difficulties of jointing, and the increased cost of insulation, when the outer conductor is required to have the same resistance from the earth as the conductors of either of the separate cables. Where very high pressures are used, and accidents might arise from the handling of the cable, the fact that the outer conductor, which alone is accessible, is very nearly at the same potential as the earth is a great safeguard; but this state of affairs only continues so long as the insulation of all parts of the circuit is perfect, unless the outer conductor itself is in some way connected to earth.

The fact that any leakage from the inner conductor must be to the outer one, and that it is therefore of

the nature of a short circuit, is claimed as a safeguard against fire in ships or buildings wired with these cables, since the circuits can be protected by fusible cutouts, and any excessive leakage from the inner conductor will break the fuse and stop the supply of current.

As regards the rectangular sectioned conductor, Professor George Forbes, in a paper on "The Prevention of Heating of Conductors," read before the Society of Telegraph Engineers in 1884, showed that strips or sheets of comparatively thin metal could, for the same rise of temperature, carry much heavier currents than round wires, and advantage is sometimes taken of this fact when the conductors are bare; but when they have to be covered with a continuous coating of insulating material, the increase in the cost of the insulation will more than counterbalance any gain due to the smaller weight of copper required to carry the current.

The jointing together of two conductors is an operation which has frequently to be performed, the method adopted depending on the size and shape of the conductor, and on whether the joint is to be insulated or not; but in all cases the first desideratum is, that the surfaces in contact shall be of considerable area, and that the contact itself shall be as perfect as possible, so that there may be no undue heating owing to any increase of resistance at the joint. With very large conductors, or conductors that have not to be covered with insulating material, the joint may be made by securely clamping the two ends together, care being taken that the surfaces are well cleaned and tinned; and this plan is also adopted in many cases where, for testing or other purposes, it is desirable to be able to break the joint at any time. The general method is, however, to connect the two conductors together by

the use of solder, supplemented when they are to be subjected to tensile strains by binding them with wire, splicing them, or enclosing the ends in special couplings.

An excellent joint for an overhead solid wire is made as shown in Fig. 19, in which the end of each wire

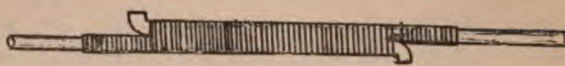

FIG. 19.

is bent up, and the two wires fixed side by side in a vice and tightly bound with binding wire, and the whole soldered together. The binding wire should by preference always be of the same material as the two wires which are being jointed, and if the wires are of hard drawn copper, care should be taken to heat them only just enough to make the solder run freely; as the use of a very hot iron, or a long-continued application of the heat will weaken the wire very considerably. For stranded conductors couplings are sometimes used, such as the one shown in Fig. 20, which consists of a

FIG. 20.

tubular piece of metal enlarged in the middle so as to form a double cone, and provided with an opening at the centre. The stranded conductor is pushed through the hole at the end and brought out at the central hole. It is then doubled back on itself, and is pushed back through the central opening, and pulled so that it jams itself tight in the cone-shaped coupling. When both conductors are fixed in this way, solder is run in

through the central hole so as to keep them in place and improve the contact.

When the conductor has to be insulated, it is important that the joint shall be as nearly as possible of the same diameter as the conductor itself, and that it shall present a perfectly smooth surface, a result which can best be obtained by the following methods:—

For a solid wire or a 7-strand conductor, the scarf joint shown in Fig. 21 is the best to use. Each conductor, if stranded, is soldered up into a solid wire, and the ends are filed to a long bevel so as to obtain a large surface of contact. The two conductors are then clamped together in a vice, bound tightly together

FIG. 21.

with tinned copper binding wire of small diameter, and soldered; after which the surface is smoothed by filing, so that there are no projections which may pierce the insulation. Resin should always be used as a flux, either raw, or dissolved in spirits of wine, when it takes the form of a thin paste; and the wires should be carefully cleaned before being bound together, so as to ensure that the solder will take freely on them.

For conductors of 19 strands or more, either a married or a telescope joint may be made. To make a married joint, a few turns of binding wire are wrapped round the conductor to keep the strands in place, and the outside wires are then turned back so as to expose the central strand. This is soldered up solid and scarfed, and the central strands of the two conductors are

jointed in the manner already described. The outside wires are then cut off to suitable lengths, alternate ones on each conductor being short and long (Fig. 22), and the two sets of wires are laid on over the central

FIG. 22.

strands, so that a long wire of one set butts up against a short wire of the other set. By this means half the joints in the separate wires are at each end of the joint in the conductor. The joint is then whipped with

FIG. 23.

binding wire at each end, and soldered (Fig. 23), and the surface smoothed up with a file. In very large conductors, where flexibility is wanted, the marrying may be repeated; as for example, with a 61-strand conductor, a scarfed joint may be made of the 19 central strands; the surrounding layer of 18 wires

may then be married together, the joints being arranged to come a couple of inches or so beyond the scarf on each side, and the surrounding layer of 24 wires may be married, so that the joints come a few inches outside these again. In each case the joint is only soldered just at the place where the separate wires are butted together, and by this means a joint can be made which can be bent about without much difficulty.

To make a telescope joint, the outside wires of one conductor and the inside wires of the other are cut off short (Fig. 24), a binding being put on first to keep the

Fig. 24.

strands in place. The central strands *a* are soldered up solid, and the outer strands *b b* are laid up again in place, so that they form a hollow cylinder, into which the projecting end *a* is pushed. A few turns of binding wire are put on over the wires *b b* to hold them firmly in place, and the joint is then soldered.

Besides the straight joint between two conductors, there is also the T joint, where a smaller wire is branched off from a main cable. If the branch wire is a solid wire it may be wrapped spirally round the larger conductor, and soldered to it; but care must be taken that the branch wire is not soldered right up to the point where it leaves the larger conductor, as it is then apt to get broken off, if bent. One turn of the

spiral may be left unsoldered, or the wire may be laid in lengthwise of the strand for half an inch or so (Fig. 25). When the branch is a 7-strand conductor, the wires should be unstranded, and three of them

FIG. 25.

laid up spirally around the main conductor in one direction, whilst the other four are laid up round it in the reverse direction (Fig. 26); the ends only of these spirals being soldered, so as to permit of the branch

FIG. 26.

being bent to one side or the other, without danger of breaking off any of the wires.

When both conductors are large, it is better to make a Y joint rather than a right-angled T joint. This is done by soldering both conductors up solid, scarfing the branch conductor, and filing a recess in the main conductor, into which the scarfed end will fit. The

two conductors are then bound together and soldered, as shown in Fig. 27.

The joints in the inner conductors of concentric cables are made in much the same way as joints in ordinary single-core cables, but the outer conductors require somewhat different methods. For a straight joint the inner conductor is scarfed or married accord-

FIG. 27.

ing to its size, and is then insulated; the wires forming the outside conductors having been turned back out of the way. A sleeve of tinned copper is then placed over the inner insulation, and the outer wires are laid up over it, married, bound with binding wire, and soldered in the way already described.

For a T joint the wires of the outer conductor are

FIG. 28.

cut through and turned back, the inner conductor is branched off and insulated, and a sleeve (Fig. 28) is folded over the insulation, so that the branch wire passes out clear through the central hole. The outer conductors of the main cable are then laid up, bound and soldered to the copper sleeve, and the outer wires of the branch are separated into two sets, and laid in

spirally over the sleeve, as shown in Fig. 29. The making of such a joint requires very great care to avoid injuring the inner insulation, whilst making the

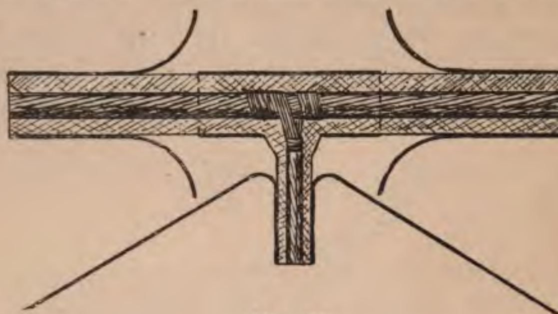

Fig. 29.

joint in the outer conductor, and takes longer and is more difficult to make than two joints in separate conductors. In the Andrews system of concentric wiring,

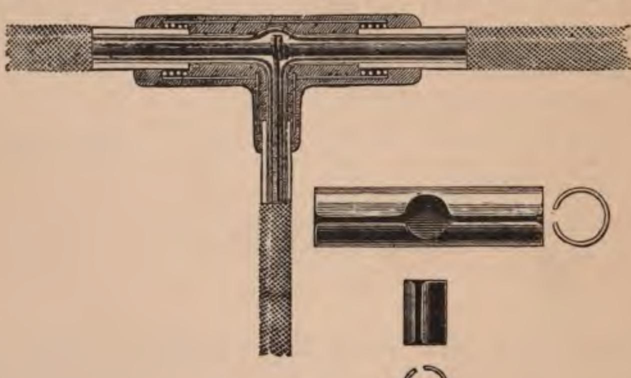

Fig. 30.

the inner joint is made as already described, it is then insulated, and over it are placed two copper sheaths which together make a T piece (Fig. 30), and enclose

the ends of the outer conductor, which in this system is connected to earth. An iron mould is then fixed round the joint by screws, and a molten metal with a low fusing point is poured into it; the mould when the joint is cold is removed, leaving the sleeves and a short length of each outer conductor beyond them enclosed within a mass of metal.

CHAPTER VII.

Insulating Materials.—Air Insulation.—Objections to its Use.—Resistance of Bare Wire Circuits; of Solid Insulators; of Insulated Cables.—Effect of Temperature on Specific Resistance of Insulators.—Effect of Pressure on Insulation Resistance.—Minimum Resistance of Circuit for fixed Percentage of Waste by Leakage.—Shocks due to Faulty Insulation; to Electrostatic Charge; to Condenser Current.—Disruptive Discharge.—Tests on Breaking Down Pressures.

When a generating and receiving apparatus are connected in a circuit in which a current is passing, it is necessary to insulate the conductors which form the connecting link between them, so as to prevent the current from finding any other path by means of which it can return to the generator, without first passing through the receiving apparatus. This insulation may be effected by surrounding the conductor along its whole length by a material or materials offering a very high resistance to the passage of the current, such as dry air, glass, ebonite, porcelain, wood, slate, mica, silk, cotton, or other fibrous materials, paper, india-rubber, gutta percha, and a variety of oils, waxes, and resinous or bituminous compounds. Some of these, such as wood, silk, cotton, paper, etc., lose their insulating properties to a very great extent when damp; and as there is always a certain amount of moisture in the atmosphere, it is necessary to protect such substances, when used as insulators, from exposure to the air by means of a waterproof covering. Besides preventing leakage sufficient to cause an appreciable waste of energy, or to give an unpleasant shock to any one touching a part

of the conducting circuit, the dielectric should be of such a kind as will allow of the insulated conductors being handled with impunity, and of sufficient thickness to prevent a disruptive discharge from one conductor to another, or from either to the earth.

There are two distinct methods by means of which it is sought to obtain these results: in one the conductor is supported at intervals on blocks of insulating material, and elsewhere is surrounded by air; and in the other the conductor is completely enclosed in a continuous covering of insulating material. The former may at first sight appear the more advantageous, since air is a cheap form of insulator; but unfortunately the air is not as a rule dry, and the film of moisture which condenses on the surface of the insulating support (especially when the latter is itself not perfectly clean), forms a fair conductor of electricity; and thus causes the insulation of a bare wire line to be very low in damp weather when the number of supports is large. There is also the danger of a short circuit between two conductors, which may be caused by their swaying so as to touch one another, or by some conducting material falling on them so as to bridge from one to the other. The conductor being bare, it must be placed in such a position that it cannot be touched accidentally by linesmen or others; unless the pressure is so low that no harm could result from a shock from it. When high pressures are used, there is the further disadvantage that the sparking distance through air for equal pressures is considerably greater than that through other insulating materials, and that this sparking distance is greater still when there are dirty surfaces over which the spark may travel. In the majority of cases one or more of these reasons make it impossible to take advantage of the cheapness of air insulation;

and continuously insulated conductors have therefore to be used.

The insulation resistance of any air-insulated bare wire circuit depends entirely on the number of supports, and on the resistance of each one of them; and as the greater part of the leakage which takes place at each support is over the surface of the insulator, this resistance is by no means constant, but varies with the state of the surface, whether clean and dry, or dirty and wet. When the surface is clean and dry the resistance may be very high; and even when wet, if the surface is clean, as happens sometimes after very heavy rain, a good test may be obtained; but when the insulators are dirty and the air full of moisture, the result is different, the insulation resistance under these conditions falling off very considerably. The shape of the insulating support is arranged so as to give as great a length of surface as possible, over which the leakage current must pass before it can get from one conductor to another, or from either to earth; and the supports are fixed in such positions as will allow of the smallest amount of dirt collecting on them. Besides leakage over the surface, there is also a certain amount which passes through the body of the insulating material, the resistance to which is proportional to the mean length of the current path, and inversely proportional to the area over which the current can spread itself, following therefore the same law as the resistance of all conductors.

The calculation of the resistance of any insulator from its dimensions gives less certain results, owing to the fact that the specific resistance of most insulating materials varies much more than that of good conductors; indeed, many of the insulating materials named above can hardly be said to have a definite

specific resistance, owing to the difficulty of reproducing them under exactly the same conditions at different times; and this is particularly the case with those materials whose power of absorbing moisture is appreciable. The insulation resistance of a cable covered with such a material cannot be predetermined with any great degree of accuracy; but with materials whose specific resistance can be relied on, the resistance of the cable can be calculated, if we assign correct values to the length or thickness, and to the area of the covering. These dimensions are obtained in the

FIG. 31.

following way for circular conductors:—Referring to Figure 31, which shows a transverse section of the insulated conductor, we see that for unit length, as we get farther from the centre, the area of a layer of insulating material increases, and that therefore successive layers of the same thickness will not add equally to the insulation resistance. Suppose then that the insulating material is divided up into a large number of concentric layers of varying thicknesses such that each layer offers the same resistance ρ, and that there are n such layers, so that $n\rho$ is the resistance of the cable; then, if d_m and d_{m+1} are the internal and external diameters of any layer, the resistance

$$\rho = \frac{(d_{m+1} - d_m)}{2\pi d_m l} \times s,$$

[redacted]

where s is the specific resistance of the insulating material and l the length of the cable. This equation may be written

$$d_{m+1} = d_m\left(1 + \frac{2\pi\rho l}{s}\right)$$

which shows that the outer diameter of any layer, whose resistance is ρ, is equal to the inner diameter of the same layer multiplied by a constant $\left(1 + \frac{2\pi\rho l}{s}\right)$. Applying this to find the outer diameter d_{m+2} of the next layer, the inner diameter of which is d_{m+1}, we get $d_{m+2} = d_{m+1}\left(1 + \frac{2\pi\rho l}{s}\right) = d_m\left(1 + \frac{2\pi\rho l}{s}\right)^2$. By similar reasoning we see that the outer diameter of the nth layer is expressed by $d_{m\times n} = d_m\left(1 + \frac{2\pi\rho l}{s}\right)^n$. Putting D the outer diameter of the insulated conductor for $d_{m\times n}$, and d the diameter of the conductor for d_m, we get $D = d\left(1 + \frac{2\pi\rho l}{s}\right)^n = d\left(1 + \frac{2\pi R l}{sn}\right)^n$, where $R = n\rho$ is the insulation resistance of the cable. By substituting $\frac{1}{x}$ for $\frac{2\pi R l}{sn}$ we can write the equation thus

$$D = d\left(1 + \frac{1}{x}\right)^{\frac{2\pi R l x}{s}} = d\left[\left(1 + \frac{1}{x}\right)^x\right]^{\frac{2\pi R l}{s}}$$

The larger the number of layers the nearer is the approach to absolute accuracy, therefore we may suppose $n = \infty$ in which case $x = \infty$; and when $x = \infty$ then $\left(1 + \frac{1}{x}\right)^x = e$, the base of the Napierian logarithms,

$\therefore D = d \times e^{\frac{2\pi R l}{s}}$ or $\frac{D}{d} = e^{\frac{2\pi R l}{s}}$, which gives

$$\log_e \frac{D}{d} = \frac{2\pi R l}{s}$$

or $R = \frac{s}{2\pi l} \log_e \frac{D}{d}$.

$$\text{But } \log_e \frac{D}{d} = 2{\cdot}3026 \ \log \frac{D}{d},$$

$\therefore R = \frac{s . \log \frac{D}{d}}{2{\cdot}728 l}$, and this equation shows that the mean value of $\frac{\text{length}}{\text{area}}$ is expressed by $\frac{\log \frac{D}{d}}{2{\cdot}728 l}$.

From this equation we see that the insulation resistances per statute mile of two cables covered with the same material will be proportional to the logarithms of the ratios of the external and internal diameters of their insulating coverings; and therefore, that with the same insulating material, this ratio will be a constant for all cables having the same resistance, no matter what is the diameter of the conductor.

The specific resistance of any insulating material is affected by temperature, but in the opposite sense to that of conducting materials; that is to say, that an increase of temperature lowers the specific resistance, and this at a much more rapid rate than it increases the resistance of conductors. For example, whereas a rise of 20° Fahr. only increases the resistance of a copper wire by rather more than 4 per cent., the same rise will reduce the resistance of some gutta perchas to about 20 or 25 per cent. of its initial value, and a rise of 40° Fahr. which would add less than 9 per cent. to the resistance of copper wire, may reduce the resistance of gutta percha to about 5 per cent. of its initial value. All insulating materials are affected in the same way, though with many of them it is to a smaller extent; but no figures can be given, either of the specific resistance or of the temperature coefficients, which can be

depended on as reliable for general use, as the variations are so considerable for slight differences in the composition of the insulating material and in the treatment it receives during manufacture. It must not be thought by this that the manufacturer is never able to predetermine the resistance of a cable; because this can be done with many materials, so long as they are mixed and treated in exactly the same way, in which case there is a definite specific resistance; but, if any change is made in the material or in the treatment of it, it is necessary to redetermine the values by experiment, as they may be altered very considerably by changes in the process of manufacture.

It has been alleged also that the resistance of a cable varies according to the pressure at which it is tested, and experiments have been made from time to time to test the accuracy of the statement. The question, as to whether the resistance decreases with increase of pressure, is of considerable importance, now that extremely high pressures are being used; because, if the effect of increased pressure, when maintained for a few minutes only, is to decrease the resistance, we may expect that the continued application of a high pressure will have a very marked deteriorating effect on the material. It is only on account of this aspect of the question that the matter has any serious practical importance, as a falling off of several per cent. in the insulation resistance of the cable at a high, as compared with that at a low pressure, is of no moment in itself; since, as a general rule, the effect of coupling up transformers, switches, cut outs, or other apparatus in circuit with the cable, is to lower the resistance of the circuit by perhaps 80 or 90 per cent.

In making comparative tests with different battery powers there are many obstacles in the way of attain-

ing really accurate results, such as the difficulty of maintaining an absolutely constant temperature, of wiping out residual charges, of maintaining the ends of the cable under permanent conditions as regards surface leakage, and the possibility of introducing errors through comparing very large and very small deflections, or through using shunts the temperature co-efficients of which may differ from that of the galvanometer coils.

Even when repeating tests with the same battery power on different days, it is by no means uncommon to get results which differ from one another by 5 per cent. or thereabouts, unless the most extraordinary precautions are taken; and one must therefore be careful not to jump to conclusions from the results of a few tests, unless the difference of insulation resistance with different pressures is very marked. Probably the most carefully conducted series of tests in connection with this matter is that which was made by Herr Heim, who compared the insulation resistances of a gutta percha core, and of two lead-covered cables at pressures varying between 21 and 460 volts. From the published description of these experiments, it appears that great precautions were taken to ensure accuracy, and corrections were made for the small temperature variations which could not be avoided, for leakage of testing instruments and leads, and for residual charge; but even in these tests there is a considerable want of uniformity in the results, the variations, when resistances were measured at different times with the same battery power, being of about the same magnitude as those which were obtained when they were measured with widely varying battery powers. For instance, with the gutta percha core, the fall of insulation resistance resulting from an increase

of pressure from 52 to 460 volts, taken as the mean of eight tests, is given as 6·6 per cent., the smallest recorded fall of insulation is 4·6 per cent., and the largest is 10·6 per cent., showing a variation between two of the tests of nearly the same magnitude as the average percentage fall due to the increased pressure.

In a similar manner one of the lead-covered cables, on which only four tests are recorded, shows a mean fall of 5·3 per cent., a maximum of 8·1 and a minimum of 2·2; whilst the other, also as the result of four tests, shows a mean of 2·9, a maximum of 3·8, and a minimum of 2·3 per cent. Comparing tests made at the same pressure but on different days, one finds that there were variations of as much as 7 per cent., even after making a proportionate correction for the small differences in temperature which are recorded; and it is difficult therefore to follow the experimenter when he concludes that "the experiments, therefore, prove that a fall in the insulation resistance does undoubtedly take place as the pressure increases in the cases of the cables that I tested." All the recorded results show a fall of resistance with increased pressure; but the fact that the figures obtained vary amongst themselves in the manner mentioned above, shows that a much larger number of concordant results is required before the proposition can be considered to be conclusively proved. As further tending to show that the question is still an open one, we may mention, that in a leading article in one of the technical journals, some tests were quoted in which pressures varying between 15 and 600 volts made very little difference in the resistance, and this difference was not always in the same direction.

Looking merely at the probability of a decrease of

insulation resistance resulting from an increase of pressure, there are one or two points which may be considered. The important question is, what is the effect on the dielectric of the continued passage of a small leakage current. We know that the flow of a current against an opposed resistance must be accompanied by an expenditure of energy which may produce either heat or chemical action, or both; and if we suppose that heat is generated, then owing to the fact that all insulating materials are bad conductors of heat, there must be a rise of temperature in the interior of the dielectric as compared with the water in which it is immersed. If the current is kept on for any length of time this might account for a fall in the value of the insulation resistance, but it is difficult to imagine such a result manifesting itself immediately the circuit is closed. Chemical action may certainly in many cases lower the resistance; but here again we are met by a difficulty, since any such fall due to chemical action is not likely to be a temporary one, but on the other hand may be expected to cause a permanent deterioration; whereas in all the experiments, the results of which have been published, a repetition of the test with a low battery power is stated to have given nearly the same resistance as was obtained before the high pressure was applied, showing that according to these tests the falling off of resistance is only temporary.

That a permanent deterioration may be caused by using a pressure nearly as great as that which would break down the insulation and cause a disruptive discharge, is certain; since experiments show that if a pressure of say 10,000 volts will break through a given thickness of insulating material immediately it is applied, then a lower pressure, say 8,000 volts, will break through the same thickness of similar material,

if the application is continued for some hours. There is, so far as we are aware, no direct proof that pressures much below the breaking-down pressures will have a similar effect, but it is quite possible that this will be the case, if only sufficient time is allowed. If we accept this view, a strong argument for high insulation resistance is furnished, since the higher the resistance, the smaller will be the leakage current, and therefore the less will be the chance of its producing any deterioration of the insulating material. Whatever conclusion may be arrived at, it is certain from the results of actual daily use of well insulated cables, that the deterioration, if it takes place at all, takes place very slowly, when the pressure is kept well below that which would break down the insulation entirely; and as an example of this, we may mention that some vulcanized rubber cables which had been in use underground for several years, at 2,400 volts, by the London Electric Supply Corporation, were recently withdrawn from the pipes in order that they might be made into concentric cables; and that these cables, which originally had an insulation resistance of about 5,000 megohms per mile at 60° Fahr, gave practically the same when tested after being taken up.

The total amount of leakage that can be allowed on any circuit depends on the permissible waste of energy, and this may be taken as a percentage of the output; and also on the maximum current which may be passed with safety through the body of any one taking hold of one conductor whilst at the same time making good earth.

The waste of energy will always be the same percentage of the total output if the insulation resistance of the whole circuit varies as the quotient of the pressure of supply by the average current; that is to

say, with the same pressure the insulation resistance may vary inversely with the current; with the same current it may vary directly as the pressure; and with the same output at different pressures it may vary as the square of the pressure. For example, suppose it has been decided that the leakage waste may equal $\frac{1}{5000}$th of the output, then the insulation resistance of the circuit R_i must be at least equal to $5{,}000 \times \frac{E}{C}$; or say with 100 volts and 100 amperes $R_i = 5{,}000$ ohms: with 100 volts and 500 amperes $R_i = 1{,}000$ ohms; with 1,000 volts and 100 amperes $R_i = 50{,}000$ ohms; and with 1,000 volts and 50 amperes (that is the same output as in the second case) $R_i = 100{,}000$ ohms.

As regards safety from shocks caused by touching one conductor, the absolute value of the leakage current which may pass through the body, must not exceed a fixed amount, and therefore the insulation resistance of the circuit should vary directly as the pressure of supply. The resistance of the part of the body in circuit and of the contacts will affect the amount of current passing, and as the value of this resistance may vary considerably according to circumstances, it is difficult to lay down a definite rule. According to experiments made by Messrs. Lawrence and Harries, the average resistance from hand to hand, when grasping a pair of metal electrodes, is about 6,000 ohms for continuous currents, and about 4,000 ohms for alternating currents. The results of experiments made by Mr. Swinburne also give a resistance to continuous currents of about 6,000 ohms, when the hands are dry; but this figure is reduced to about 2,000 ohms when the hands are moistened with dilute acid. The resistance to alternating currents, however, comes out much lower in these experiments, averaging about 1,000 ohms

only, when the resistance of one subject which was phenomenally high is left out of account.

The two sets of experiments also show a considerable difference in the amount of current which may be passed through the body without injury; Messrs. Lawrence and Harries giving an average of ·018 ampere as the value of the continuous current which becomes really painful, and rather over ·004 ampere as that of the alternating current. They also found that muscular fixation, that is the inability to leave go of the electrodes, was caused with an alternating current of rather less than ·008 ampere. Mr. Swinburne found that all the subjects of his experiments could stand more than ·018 ampere continuous current, and one actually stood ·044 ampere, and could have taken more if it had been available. With alternating currents the amperes varied from ·014 to ·030, according to the resistance of the subject, the pressure between the two electrodes being 18 volts, and under these conditions there was no difficulty in letting go.

Since, in cases of this kind, it is always best to have a large margin of safety, we may take it that there will be absolutely no danger if the current, which can pass through any one's body, does not exceed ·01 ampere continuous, or ·002 ampere alternating; and assuming the lowest value of the average resistance, viz., 1,000 ohms, we then find that the insulation resistance of the circuit should be at least $\frac{V}{\cdot 01} - 1{,}000$ for continuous currents, and $\frac{V}{\cdot 002} - 1{,}000$ for alternating currents, when V is the pressure of supply. These expressions may be written $100\ V - 1{,}000$ and $500\ V - 1{,}000$, and give the following values for the required insulation resistance of the circuit:—For

continuous currents, 9,000 ohms for 100 volts pressure, 99,000 ohms for 1,000 volts, and 199,000 ohms for 2,000 volts; and for alternating currents, 49,000 ohms for 100 volts, 499,000 ohms for 1,000 volts, and 999,000 ohms for 2,000 volts; or, neglecting the resistance of the body, 100 ohms and 500 ohms respectively for each volt of pressure. As a matter of fact, the resistance at the point of contact between any part of the body and the conductor is generally, when the contact is accidental, very considerable; and therefore the resistance opposed to the passage of the current is much higher than that given by experiments, in which the subject grasps two metal electrodes, and the current passing through the body is less; we therefore find that, with low pressures, the conductors can be handled with impunity even when the insulation resistance is lower than that named above; but there is always the chance of making a really good contact, and full precautions should therefore be taken to guard against accidents arising from this cause.

One of these precautions, which is a very self-evident one, is to reduce the amount of exposed conductor to a minimum, and to arrange the conductors, where they must of necessity be left bare, in such a manner that access can only be had to them by persons whose business it is to keep the circuits in good order, and who, one may suppose, will take proper precautions when handling them. Accidents have sometimes happened through a linesman, working on a conductor which has been put out of circuit, coming into contact with a neighbouring wire in which a current is flowing; and therefore, unless the wires of a circuit are so far removed from all other wires as to render such an occurrence impossible, it is advisable in all cases to cover them with a continuous insulating coating, which,

to be of any service, must be waterproof, so that its insulation remains unimpaired under all conditions of working.

Thus far we have only considered the case of a shock caused by faulty insulation; but, under certain conditions, it is quite possible to get a shock if contact is made simultaneously with the earth and one conductor, even although the insulation of the circuit is perfect; and not only this, but if a person makes contact with the outside covering of one cable and with earth, or with the outside coverings of both cables, a current may flow through his body. The necessary conditions for the passage of a current, when such contacts are made, always exist to a greater or less degree; but it is only when high pressures are used, in conjunction with cables having an appreciable electrostatic capacity, that the current which may pass is of sufficient magnitude to require consideration.

Let us suppose that there are two perfectly insulated conductors, each of capacity K, between which there is maintained a continuous pressure V. The difference of potential between each conductor and the earth will be $\frac{V}{2}$, and each conductor will be charged with a quantity of electricity equal to $\frac{KV}{2}$. If a contact is made between one of these conductors and the earth, there will be a rearrangement of potentials; with the result that the conductor, with which contact is made, will be at the same potential as the earth, whilst between the other and earth there will be a difference of potential V; and a current of electricity will flow through the conducting medium connecting the conductor to earth. The quantity of electricity to be transferred is the charge on the one conductor plus the

additional charge required to raise the potential of the other to V; and since each of them is equal to $\frac{KV}{2}$, the total quantity which will pass will be KV. The current flowing will have a maximum value of $\frac{V}{2R}$, if R is the resistance of the contact, and will rapidly diminish in value as the difference of potential between the earth and the conductor is reduced; so that the shock received by any person making such a contact may be very sharp if V is high, but will only last for a short time.

The case is somewhat different, however, with alternating currents, as the charge is not a steady one, owing to the continual variation of the value of the instantaneous difference of potential. When a condenser of capacity K has its plates connected to the terminals of a dynamo, or transformer, supplying an alternating current at a pressure V, and a frequency n, a current is delivered to it which may be measured by the expression $C = \frac{2\pi n KV}{10^6}$, if K be expressed in microfarads, C in amperes, and V in volts. Now any system of cables connected in a circuit is the equivalent of a condenser, or of a combination of condensers; and therefore, if we can determine the capacity of the circuit under any given conditions, we can measure the current which flows across the dielectric. Now consider the case of two insulated cables between which there is a pressure V, and let the conductor of one be connected to earth by any person making simultaneous contact with it and the earth; then, if the capacity of the other cable with respect to earth is K, the condenser current, which will flow through the body of the person making connection, will be equal to $\frac{2\pi n KV.}{10^6}$

This current may be of considerable magnitude, if the cable is long and laid underground, so that its capacity is large; for example, with a capacity of half a microfarad and a pressure of 2,000 volts at a frequency of 80, the current would be half an ampere. With an overhead cable of the same length the capacity would be much smaller, and the current, which would pass through the body of any person making contact with one conductor and with the earth, would be proportionately less; but it might still be sufficient to give a very unpleasant shock.

For similar reasons a current will pass through the body of any person making contact with the outside of the insulating covering of one cable and with earth, or with the outsides of both cables, always supposing that the outside of the dielectric is not already connected to earth through a low resistance. This is a matter of some importance with overhead cables which are carried on insulators; as, if they are sheathed with metal, or if the tapes or braiding which cover the dielectric are wet and therefore fair conductors, it is possible to get a shock by making contact with them. The current, which will pass under such conditions, may be calculated when the joint capacity of the cables is known; for instance, if there are two overhead cables, each having a capacity K as measured between their conductors and outside sheathing or braiding, and K′ as measured between their conductors and earth, their joint capacity, when the sheathing of one is connected to earth by any person making contact with it, is $\frac{\mathrm{KK}'}{\mathrm{K}+\mathrm{K}'}$, since they are equivalent to two condensers joined in series; and the condenser current will therefore be equal to $\frac{2\pi n\mathrm{VKK}'}{10^6(\mathrm{K}+\mathrm{K}')}$. When the two sheathings are

connected by any one making contact with both of them, the two capacities joined in series are equal, each being K; and the joint capacity is equal to $\frac{K^2}{2K} = \frac{K}{2}$. If now the pressure is 2,000 volts, the frequency 80, and the values of K and K′ respectively ·5 and ·015 of a microfarad, figures which may fairly represent the state of affairs on a high pressure main one mile long, we find that $\frac{2\pi n VKK'}{10^6(K+K')} = \cdot 0145$, and that $\frac{2\pi n VK}{10^6 \times 2} = \cdot 25$; that is, that a current of 14½ milliamperes would pass through the body of any person making contact with the sheathing of one cable and with earth; and a current of 250 milliamperes, or a quarter of an ampere, would pass when the contact is made between the sheathings of the two cables. When the outside of the cable is connected to earth at all times, as is the case with underground cables, or with overhead cables when not attached to insulators, this condenser current will have an easier path than through the body of any person making contact with the sheathing; and it is therefore advisable to connect to earth the outside protective covering of all overhead cables, as also any bearer wires which may be used to support them. This will no doubt increase the current flowing, when contact is made between a conductor and earth, because it increases the capacity of the cables; but it is so much easier to guard against an accidental contact with the conductor, by properly protecting all terminal connections, that this is of secondary importance.

When high pressures are used, the possibility of a disruptive discharge from one conductor to another, or from either to earth, has to be considered; and the conditions, which determine whether such a discharge will take place or not, do not depend on the actual in-

sulation resistance, but on the distance apart of the two bodies between which the difference of pressure exists, and on the power of the intervening material of withstanding the strain set up in it. In this respect air is of all insulating materials the least efficient, a pressure of only 23,400 volts being required to break down the resistance offered by an air gap of one inch between a plate and a point; but if resin oil is used instead of air, the distance that can be sparked across with the same pressure is reduced to about one-tenth of an inch.

The resistance opposed by solid insulators to a discharge is also much greater, and can best be measured by clamping a sheet of the material between two metal discs, and connecting these discs to the two terminals of the transformer or induction coil. When tried in this way, the author has seen sheets of india-rubber and gutta percha between 30 and 40 mils thick resist a pressure of 20,000 volts, and in some tests which he has recently made on rubber and gutta-percha covered wires of ordinary stock sizes, the following results were obtained:—

Of five wires, conductor 28 mils covered with rubber to a thickness of 28 mils, three broke down at 5,200 volts, and two at 6,200 volts; and with wires 36 mils diameter covered with rubber to a thickness of 36 mils, one broke down at 7,900 volts, and four at 8,400 volts. Out of a similar number of wires of 48 mils diameter covered with gutta percha to a thickness of 28 mils, one broke down at 8,200 volts, which was the highest pressure which could be obtained from the transformer in use at the time, and the others withstood this voltage for an hour and a half without failing. With thicker coverings the pressure required to break down the dielectric will probably increase rather faster than the

thickness, until it reaches something like 60 mils or thereabouts, as the difficulty of making the core perfect mechanically is greater with very thin coatings of insulating material, and the discharge takes place at some weak spot in the dielectric, at a lower pressure, than that which would be required to pierce a perfectly even sheet of the same thickness.

CHAPTER VIII.

Continuously Insulated Cables.—Requirements of Good Insulating Materials.—Importance of Durability and Permanence.—Resistance to Disruptive Strain.—Thickness of Insulating Covering.—India-rubber.—Gutta Percha.—Bitite.—Fibrous Insulating Materials.—Lead Encased Cables.—Concentric Cables.—Sheathed Cables.—Rise of Pressure and Condenser Current in Ferranti Mains.

Of the two methods of insulating conductors to which reference was made in the preceding chapter, the one which is most frequently employed is that in which the conductor is covered along its whole length with a continuous envelope of insulating material. The core thus made is then covered with a protective coating of tapes, or braiding, or with a metallic sheathing, and is then called a cable.

Many different materials are employed as the insulating medium, each having its advantages and disadvantages, and each possessing, to a greater or less degree, those qualities which are essential to the production of satisfactory working. These qualities vary according to the nature of the work which the cable is called on to perform; but in all cases it is necessary that the material, or combination of materials with which the conductor is covered, should provide a fairly high insulation; and that the resistance opposed by it to the passage of a current should remain constant within small limits under all the varying conditions of working In order that this may be so, the insulating covering must be waterproof, as moisture penetrating into it will at once cause a leakage of current; it must be mechanically strong and tough, so that it cannot

easily be torn or split; it must be flexible, so that it can be bent without cracking; it must be capable of withstanding fairly high temperatures without softening, or being in any way permanently injured; and it should be unaffected by the acids or gases with which it may come in contact. In addition to its insulating qualities it must, when used for high pressure work, be capable of offering great resistance to disruptive discharge; and to this end the material should be homogeneous. When these requirements are fulfilled, the best cable is that whose cost, bulk, and weight are least, and which can be most easily fixed in place and jointed.

As regards insulation, we have seen that the resistance of a cable per unit length depends on the thickness of the covering, and on the specific insulation resistance of the material employed, and it is therefore important that the value of this specific resistance should be high. Too much stress must not, however, be laid on the necessity of very high initial resistance; as it is better to have a medium value for this, if that value is permanent, than to start with a high resistance which is likely to be soon lowered by the strains to which the cable is subjected in ordinary working. In many cases, such as in the internal wiring of buildings or ships, the insulating covering of the cable is so much cut about for the making of joints and connections to switches, lamps, and other fittings, and so many of these latter are connected in the circuit, that the insulation resistance of the complete installation is determined chiefly by the resistance of these fittings to surface leakage; and is affected to a very slight degree by the insulation resistance of the cable itself. For instance, in an installation of 100 incandescent lamps, there will be at least 300 places where the cables are connected to

fittings of one kind or another; each of which affords an opportunity for leakage over the surface of its insulating base. Now if the resistance at each of these places is as much as 300 megohms, the joint resistance is only one megohm; and the difference that will be made by adding the leakage from the uncut parts of the cable will be very small, with the average length of wire in such an installation, whether its insulation resistance is 50 or 1,000 megohms per mile.

Although from this point of view it may appear unnecessary to use cables of high insulation resistance, there are many reasons why they should be used in preference to those having a low resistance; since, as a general rule, a cable of high resistance is more easy to manufacture with uniformity, and offers to the manufacturer a better chance of discovering by the insulation test any partial fault which may exist in it; and further, in any installation, where cables are employed whose normal insulation resistance is high, it is easier to discover and localize a fault, than if the insulation of the cables used gives a low resistance.

Uniformity of specific resistance is of great value to the manufacturer, who tests his cables, not only with a view to their passing some guaranteed standard, but as a check on the manner in which their manufacture has been carried out; as it enables him to calculate, from the known dimensions of the cable, what the resistance should be: and by comparing the measured with the calculated resistance, he can detect the existence of any flaw in the covering, or difference in the quality of the material, which, although it does not reduce the resistance below his guaranteed standard, will in time cause the failure of the cable.

The power of withstanding the breaking-down strain of a high pressure is of equal, if not greater importance

than high insulation resistance, in cables which will be subjected to such strains; and, as we have already seen, these two requirements do not always go hand-in-hand. For instance, air is a most perfect insulator, in fact its insulation resistance is so high as to be practically unmeasurable; but it is also the dielectric which is least able to withstand the disruptive strain of a high electric pressure: and although the difference is not so marked, there are with such materials as rubber, gutta percha, and ebonite, many qualities, which, although they have a higher specific resistance than others, are yet less able than them to withstand disruptive strain.

When we consider cables insulated with the same material, but having conductors of different diameters, we find the same thing; since, to make the insulation resistances equal, we must keep the ratio of the outside to inside diameter of the insulating sleeve constant, whereas the same power of resisting disruptive discharge is obtained by maintaining the absolute thickness of the dielectric constant. Thus a cable with a larger conductor will stand a much higher pressure without breaking down, than one having a smaller conductor, and the same insulation resistance; and, if both are so made that they will stand the same pressure, then the smaller one will have a higher resistance.

There are then three separate points which must be taken into consideration in determining the proper thickness of insulating material, viz.:—the prevention of leakage, of disruptive discharge, and of mechanical injury to the dielectric. For conductors of different diameters insulated for equal resistances with the same material, the thickness of the dielectric must bear a definite proportion to the diameter of the conductor: for equal resistance to disruptive strain, the thickness of the dielectric is practically constant for all

diameters of conductor: and lastly, for mechanical strength the thickness must be increased as the conductor is made larger; but in this case, it is not found necessary to increase it in proportion to the diameter. The question then arises as to what is the best rule to work on in deciding the amount of any insulating material that should be used; and this must necessarily depend on the material, and on the conditions of working. With dielectrics which have a high specific resistance, the thickness is generally settled by considerations of mechanical strength when low pressures only are to be used; as in this case the insulation resistance will probably be ample with any thickness which is practicable. When high pressures are to be used, the same consideration will be the important one with large conductors; but with small ones, it will be the thickness required to resist the breaking-down strain due to the high pressure. With materials of low specific resistance, the thickness required for insulation resistance becomes more important, and may, except for very small conductors, outweigh all other considerations; and with materials which are not homogeneous, and in which air passages may exist, the prevention of disruptive discharge due to high pressures is the most difficult matter to deal with.

The continuously insulated conductors, which are in use at present, all belong to one or other of two main classes; in one of which the dielectric material is unaffected by the presence of moisture, being a homogeneous mass whose power of absorbing water is very small; whilst in the other the dielectric material must be supplemented by a watertight metallic envelope, since it is composed of fibrous material which absorbs water readily. The materials used to insulate cables of the first class are india-rubber, either by itself or mixed

with other materials, gutta percha, and a preparation of bitumen which has been called bitite; and for cables of the second class, jute, hemp, cotton, or paper impregnated with oils, waxes, or bituminous and resinous compounds, are usually employed.

Of these materials, the one which is best adapted to withstand the strains to which an electric light cable is subjected is india-rubber, when of good quality and properly applied; as its specific resistance is high, and its power of withstanding the strains due to high pressure greater than that of almost any other insulator, either solid or liquid; and, further, it is thoroughly waterproof, capable of standing changes of temperature over a wide range without injury, and mechanically strong, tough, and flexible. So far as the comparatively short time during which it has been in use for electric light work will allow us to judge, it is also very durable; for example, several miles of cable which were laid eight years ago at Silvertown, and have been since then in constant use underground running arc light circuits at a pressure of 500 to 600 volts, are now in perfect working order, and have so far needed no repairs. The experience of the Hastings Electric Light Company extends over a period of nearly the same length, as they commenced to lay rubber cables underground in 1884; and although working on the Brush series system with a pressure of about 1,600 volts, none of this cable has had to be replaced, nor has it given any trouble. Similar results have been obtained during the last four or five years by other companies, operating their circuits in many cases with alternating currents of 2,000 volts; and as there are now many miles of such cable in use, each year will make us more able to determine accurately the probable life of a rubber cable, when constantly subjected to the strains of high pressure.

India-rubber has, however, one great disadvantage, which is, that it is expensive; and it is on this score that objection is often raised to its use; but, if this is left out of consideration, and the matter looked at entirely from the technical point of view, there is no doubt that rubber cables are the best, so far as our present experience goes. The first cost of the cable is, however, a serious matter, and must naturally engage the attention of all engineers; since the most economical cable should be chosen on lines similar to those which determine the economical area of the conductor; that is, that cable should be used, for which the sum of the interest on capital outlay and of the cost of maintenance and depreciation is a minimum. This is a problem for which the complete data cannot be furnished for some years to come, and for the present therefore it cannot be discussed further.

Gutta percha, although excellently well suited to the requirements of submarine telegraphy, is unsatisfactory on account of the low temperature at which it softens, and it has therefore been very seldom employed as an insulator for electric light work, where heavy conductors and large currents are required. It further has the disadvantage that, when exposed to the atmosphere, it becomes brittle and cracks. If kept under water at a temperature between 40° and 80° Fahr., it is an excellent insulating material; and, when protected by a good covering of tapes and Stockholm tar, and laid underground where it can be kept at a fairly constant temperature in a moist atmosphere, it gives satisfactory results in telegraph and telephone work. For electric light cables it has been sometimes used under water, or in very damp places; and at the Great Western Railway installation it has been used for the underground mains; but unless under water,

the sectional area of the conductor must be increased so as to prevent any appreciable heating, as otherwise the conductor is liable to sink through the insulation and destroy the cable.

Bitite, the insulating material used by the Callender Company, is a preparation of bitumen; and, like all other bituminous materials, is difficult to prepare so that it is neither so hard and brittle as to crack when bent, nor so soft as to allow of the conductor becoming uncentred. It is therefore open to objection from a mechanical point of view, and is liable to get damaged in drawing into or out of trenches, especially when there are frequent sharp bends. Electrically its specific resistance is not very high, and it does not appear to stand the strains due to high pressures so well as many other insulating materials; so that its use has been confined chiefly to low pressure installations. Bitite cables are often further protected by being laid in troughs, which are filled up solid with a bituminous compound, and this treatment of them appears to give the most satisfactory results.

The cables of the second class, which are most generally used, are those in which the conductor is covered with fibrous material impregnated with an insulating compound, and the whole enclosed in a lead tube. Cables made in this way are, as a general rule, considerably cheaper than good rubber cables; but they have, in the author's opinion, various disadvantages, which render them inferior from both a mechanical and an electrical point of view; and it must therefore be a question for the engineer to decide in each case as to whether the more expensive cable is worth its price to him or not.

The insulation resistance of these lead-encased cables depends on the complete expulsion of all moisture from

the fibrous material before it is surrounded with lead, and then on the lead casing as a means of preventing fresh moisture from being absorbed. Now, it is well known that the continual application of heat to a fibrous material has the effect of taking all the strength out of the fibre; and there is therefore great danger, either that the moisture will not be expelled sufficiently, or that the fibre will be unduly weakened. The varying amount of moisture in the fibrous material, before it is immersed in the bath of compound, prevents a uniform treatment from giving equal insulation resistances for cables of similar dimensions; and this makes it more difficult to decide whether an insulation resistance which is below the average is due to a local fault or to a uniformly lower specific resistance; thus taking away considerably from the usefulness of the insulation test.

The hygroscopic nature of the insulating material makes it ready to absorb moisture again, whenever it is exposed to the air; and great precautions must therefore be taken, when making joints or terminating a cable, to prevent this absorption from taking place, as otherwise the insulation resistance will be lowered. From the same cause any small flaw in the lead will sooner or later make a fault; and it is very difficult to ensure that the lead casing is perfect even when it leaves the factory, as the flaw may be so small that the lowering of the insulation is hardly appreciable, until after the lapse of a much longer time than that during which the cable is under test in water. There is also the further danger that the lead may be damaged during the process of laying the cable, or that when laid it may be destroyed by chemical action.

The durability of lead pipes is very variable when laid in the soil; and although we sometimes hear of

short lengths of lead pipe, or of some of the early lead-covered telegraphic wires, being dug up and found to be in excellent condition, we seldom hear of any long length which has remained perfect; and experience has unfortunately shown us that under certain conditions the effect of chemical action is very rapid. A striking instance of this is the rapid failure of many cables covered with pure lead, and laid in creosoted wood conduits, which has caused so much trouble in America; but in this particular case, a partial remedy has been found in alloying the lead with a small percentage of tin, which has given much better results.

As regards the resistance to disruptive discharge, the fact that the dielectric is not homogeneous, and that the component parts have different rates of expansion and contraction, causes cracks and small air paths in the insulation, and these offer a much lower resistance to the discharge. This has been a great source of trouble on arc light circuits in America, and it has been found necessary, on account of the frequent occurrence of faults, to increase the thickness of the dielectric very considerably, making it first $\frac{5}{32}$ of an inch instead of $\frac{3}{32}$ of an inch, and finally $\frac{3}{16}$ of an inch, which has now become an ordinary thickness.

Notwithstanding these disadvantages, the lead-encased fibrous cable is very extensively employed on account of its lesser cost, more especially for low pressure distribution; and, as time alone can show what class of cable is really the most economical to lay down and maintain, we must be content to wait for a few years, when, no doubt, from the experience gained during that time, there will be ample data on which to decide the question.

When considering the relative advantages of the various shapes which might be given to the conductor

(see Chapter VI.) we pointed out that the cost of insulation was considerably affected by varying the shape; and that, in many cases, the economy in the weight of the conductor, obtained by using a tubular or rectangular form, was more than counterbalanced by the increased cost of insulation. If the same insulation resistance per mile is required, the weight of insulating material increases in proportion to the square of the surface to be covered per unit length of the conductor, and any increase in the amount of surface has therefore a very decided effect in augmenting the price. This follows from the fact that the ratio $\frac{D}{d}$ of the outside and inside diameters of the dielectric is a constant for equal resistances; and that the weight of the dielectric is proportional to $D^2 - d^2 = d^2 \left\{\left(\frac{D}{d}\right)^2 - 1\right\}$, that is, is proportional to d^2. This has an important bearing on the cost of concentric cables, whose outer conductor is insulated from earth; since the surface to be covered is so much greater. For example, suppose that we wish to replace two separate cables by a concentric cable, and that the same resistances are required in the latter as in the former, both between one conductor and the other, and between either conductor and the earth. If d is the diameter of the conductor, and a ratio $\frac{D}{d} = 2$ gives the desired resistance R_i, the weight of the dielectric, being proportional to $D^2 - d^2$, is equal say to $3\,Ad^2$, when A is a constant depending on the length of the cable and the specific gravity of the insulating material. The weight of the dielectric in the two cables will therefore be $6\,Ad^2$, the resistances between the two conductors $2\,R_i$, and between either and earth R_i. Now compare this with the concentric cable; first,

the ratio of $\frac{D_1}{d}$ for the inner insulation must have a bigger value, which may be calculated thus:—

$$\log \frac{D_1}{d} : \log \frac{D}{d} = 2\ R_i : R_i, \text{ and since } \frac{D}{d} = 2$$

$$\log \frac{D_1}{d} = 2 \log 2, \text{ or } \frac{D_1}{d} = 4.$$

The weight is equal to A $(D_1^2 - d^2) = 15\ Ad^2$, or five times what it was before. If we consider the outer conductor as a tube of equal area to the inner conductor, and call its outer diameter d_1, we get $d_1^2 - D_1^2 = d^2$ or $d_1 = 4{\cdot}12d$. Now to get a resistance R_i from earth, the outer diameter of the dielectric $D_2 = 2d_1 = 8{\cdot}24d$, and the weight $= Ad^2\ \{(8{\cdot}24)^2 - (4{\cdot}12)^2\} = 50{\cdot}9\ Ad^2$. The total weight of the dielectric in the concentric cable is thus equal to $65{\cdot}9\ Ad^2$, or nearly eleven times the weight of insulating material in the two single cables.

No concentric cables are actually made to give equal insulation resistances, on account of the enormous expense which would be incurred, but it is often necessary to make them with the same resistance to disruptive strain; that is to say, to make the thickness of the dielectric proportional to the difference of potential at its two surfaces; and although in this case one does not find such an enormous difference in the weights of the insulating material, yet the weight in the concentric cable is often two or three times that in the two separate cables.

The relative merits of concentric, as compared with two separate cables have attracted a good deal of attention; the former being advocated especially for use with high pressure alternating currents. There is a good deal to be said on both sides of the question, and various points have to be taken into consideration. The

concentric cable has certain advantages as regards the question of induced currents in neighbouring wires; since, so long as the insulation is good, the inductive effect on a neighbouring wire is nil, owing to the one conductor being concentric with, and entirely enclosed by the other. This is an important matter when telegraph or telephone wires run parallel with and close to a circuit carrying alternating currents; but, so far as the author is aware, no trouble has been experienced in this respect, when two separate cables have been laid close together, as for instance when drawn into the same pipe.

In the matter of safety to the public, the concentric cable is better, under certain conditions of working, than two separate ones; since, if the capacity of the outer conductor with regard to the earth is considerable, and the insulation of all parts of the circuit is good, the mean potential of the outer conductor is the same as that of the earth; and the greatest difference that can exist between the two, is that due to the fall of pressure caused by the current flowing in the cable. This state of affairs is however entirely changed if the insulation of any part of the circuit becomes faulty; for example, suppose a fault occurs in some part of the transformer coil, the point at which the leak exists will be brought to the same potential as the earth, so that between the outer conductor and earth there may, under such circumstances, be a considerable difference of potential. It has sometimes happened, when a fault of this kind has occurred, and the outer conductor has been separated from the earth by a thin coating of insulating material, that a discharge has taken place between the two which has broken down the insulation; and the possibility of the occurrence of faults of this kind therefore makes it

necessary that the insulation of the outer conductor should be as thick and as good as that between the inner and outer.

To overcome this difficulty, and to ensure that only a small difference of potential can ever exist between the outer conductor and the earth, it has been proposed that they should be electrically connected at some part of the circuit; and this plan has been adopted by Mr. Ferranti in the mains of the London Electric Supply Company. With two separate cables laid underground, so that their outer coverings are earthed, the danger of receiving a shock is very remote except when some part of the conductor itself is handled; and this same danger occurs on a circuit in which the cables are concentric, unless the concentric principle is carried right through to all connections to transformers, switches, etc.; that is, unless the inner conductor and all apparatus to which it is connected are entirely enclosed at all points of the circuit within the outer conductor. When this is the case, and the outer conductor is earthed, it is difficult to imagine any arrangement which could give greater safety; but so far, in none of the circuits at present in use has the concentric system been so completely carried out, and therefore the degree of safety obtained by the use of concentric cables is not much greater than that which can be got, when separate cables are used and the ordinary precautions are taken.

A difficulty that is met with in the use of concentric cables is, that it is not possible to ascertain the condition of the insulation between the two conductors, without first disconnecting from them the dynamo, transformers, or other apparatus in the circuit; and therefore one cannot test the insulation when the circuit is working. This is a serious disadvantage of concentric, as compared

with separate cables; as, with the latter, a continual test may be kept on the circuit, which will in many cases give warning, before a fault is sufficiently developed to prevent the circuit from being worked, and thus afford an opportunity of localizing and repairing the fault before any interruption of the lighting takes place.

When lead covered or armoured cables are used for alternating currents, it is always better to use concentric cables; as, when a single conductor cable sheathed with metal is used, there is an appreciable waste of energy from the induced currents in the sheathing; whereas this waste does not occur with concentric cables, owing to the equal and opposite currents in the two conductors neutralizing one another's effect. M. Ch. Jacquin has published the results of some experiments, in which he compared the energy expended in sending an alternating current, whose frequency was 50, through an armoured cable, with that required to transmit through the same cable an equal steady continuous current. He found that, if the sheathing was well insulated, the energy lost in the cable was 18 per cent. greater for the alternating than for the continuous current, and that if the sheathing was uninsulated, which is generally the case, this figure was increased to 28 per cent. When a higher frequency is used, this increased loss in transmission becomes greater, and may, with frequencies which are commonly employed, add as much as 50 per cent. to the loss in the conductor.

In the matter of jointing, greater difficulty is experienced with concentric than with single conductor cables, especially with T-joints; and, for this reason, the connections are more often made in a special joint box in preference to making the usual soldered and insulated joint.

Before leaving the subject of concentric cables, we may mention two effects, due to their capacity, which have been more especially noticed in the long concentric mains laid by Mr. Ferranti from Deptford to London, viz., that there is, under certain conditions, a very appreciable increase of pressure at both the primary and secondary terminals of a step-up transformer, when connected to these mains, above that which exists when the secondary circuit of the transformer is disconnected from them; and that a current of considerable magnitude flows across the dielectric between the inner and outer conductors. Dr. Fleming has given the results of some experiments on these mains in his paper "On some effects of alternating current flow in circuits having capacity and self-induction." When current was supplied by a step-up transformer to the mains at a pressure of about 10,000 volts, and a frequency of 67, it was found that the ratio of the pressures at the secondary and primary terminals was greater than the multiplying ratio of the transformer coils, by an amount equal to about 5 per cent. when a current of 30 ampères was delivered into the mains, and to from 10 to 15 per cent. when the circuit was unloaded: further, that a current of nearly 16 ampères entered the main, when none was delivered to the transformers at the far end; and that, when 30 ampères were delivered at the far end, the current entering the main was from 10 to 15 per cent. greater. This current is the resultant of the current delivered at the far end of the main, and the condenser current, which differs 90° in phase from it; and the latter may therefore be calculated by taking the square root of the difference of the squares of the in-going and outgoing currents. The condenser current in any cable may, as we have already seen, be calculated indepen-

dently when the capacity, pressure, and frequency are known, being equal to $\frac{2\pi\, n\, K\, V}{10^6}$ where

n is the frequency,
K the capacity in microfarads,
V the pressure in volts.

Of course these phenomena may also occur with two separate cables; but they are not as a rule so marked, owing to the fact that the capacity is not so great. The length of main experimented on, when the results quoted above were obtained, was 11½ miles, and the capacity between the inner and outer conductor for this length was 4 microfarads, when measured by the ordinary steady charge method; this latter figure being somewhat greater than the capacity as calculated from the condenser current by the formula given above.

CHAPTER IX.

India-rubber.—Whence Obtained.—Method of Collecting.—Pure Rubber.—Vulcanized Rubber.—Pure Rubber Cables.—Compound Rubber Cables.—Vulcanized Rubber Cables.—Joints in Rubber Cables.—Okonite.—Gutta Percha.—Joints in Gutta Percha Cables.—Bitite.—Joints in Bitite Cables.

INDIA-RUBBER, which is extensively used for the continuous insulation of electrical conductors, is a gum obtained from a milky sap, existing in the middle layers of the bark of certain trees and creepers, which grow in various parts of South America, Africa, and the East Indies. It is obtained by making incisions in the bark, or by stripping off the outer layer of it; or, as is often done on account of the larger immediate yield, by cutting down the trees; and the sap which exudes is collected, and treated in different ways to make it coagulate. The quality of the gums received from different districts varies very much, the variation being partly dependent on the tree from which it is obtained, and partly on the method of collection and the after treatment it receives at the hands of the natives.

The best quality of rubber is that obtained from Para, after which may be placed the East Indian, Central American, and African, in the order named; and much of the superiority of Para rubber is attributed to the more careful way of collecting it, and to the method of coagulating the milk, by exposing it in thin layers to the smoke of a fire made of wood and certain native nuts. This treatment appears in great measure to neutralize the effect of a decomposing agent, which exists in the gum as collected from the trees, and acts so rapidly, that much of the rubber, which is not so

well dried, arrives in England in a partially rotten state.

The best qualities of Para rubber in the raw state have great tensile strength and elasticity, and are not nearly so liable to decompose as after they have undergone the processes of washing and mastication; but, unfortunately, the raw rubber cannot be easily applied to the various purposes for which it is required; and for convenience in handling, and to remove the impurities often found mixed with it, it is necessary to submit it to the processes of washing and mastication, in which the rubber is broken up, and its strength and elasticity destroyed to a great extent. The masticated rubber may be made into sheets and strips, and it is in this latter form of strips wound spirally round the conductor that the pure rubber is used for insulating purposes. Pure strip made from the best qualities of raw rubber has a high specific insulation resistance, but it is very susceptible to changes of temperature; and the application of only a moderate heat hastens the decomposition of the rubber, which is due to some solvent agent contained within itself, and which causes it, when exposed to light and the action of the atmosphere, to become viscid, and afterwards to assume the form of a brittle resin.

All the conductors used for telegraphic work in the early days, when insulated with rubber, were covered with spiral wrappings of tape, the overlapping strips being joined together by the use of naphtha, or by the application of heat. This treatment, although it made the insulating covering fairly watertight, helped on the early decomposition of the rubber; and it was this rotting of the rubber which was the chief cause of the preference accorded to gutta percha; a preference which still appears to exist, although certainly without any

adequate reason, so far as land telegraph work is concerned, now that such improved results are obtained with vulcanized rubber insulation. The use of vulcanized rubber insulation was proposed rather more than thirty years ago, and patents were taken out for several methods of covering conductors with a coating of this material; but it was not until 1868 and the following years that it was used to any great extent, and at that time something like 4,000 knots of submarine cable, with vulcanized rubber core, was laid, much of which is still working, after being more than twenty years under the sea.

So far as electric lighting is concerned, it is only within the last three or four years that this class of cable has been at all extensively employed, although small quantities were occasionally used for special work before this time; but now it is recognised as one of the best, if not the best, material for the insulating covering of cables and wires, more especially when currents are distributed at high pressures, and great strains are therefore put on the dielectric. In this connection we may quote the opinion expressed by Herr Kopsel, as the result of experiments with high pressures carried out last April at the works of Messrs. Siemens and Halske, at Charlottenburg, which was, that the only possible solid insulator for high pressure work was specially prepared vulcanized India-rubber.

On account chiefly of the simple machinery required and the ease of manufacture, cables and wires insulated with pure rubber strip were almost universally employed in the earlier days of electric light work; and many hundreds of miles of such wires were fitted up in houses and other buildings, and on board ship. The conductor was as a rule wrapped first with cotton thread, and over this one or more layers of pure

rubber strip were laid on spirally, the core thus formed being afterwards taped and braided. The objections to this kind of insulation are, that the covering is not waterproof unless the strips are made to stick together by the use of a solvent, or by the application of heat; and both these methods are harmful to the rubber: that it does not stand either very low or very high temperatures without injury: and that the covering has not sufficient mechanical strength to allow of the wire or cable being handled without risk of damage. This want of mechanical strength was felt more especially with the larger cables, which, owing to the great expense of putting on a thick coating of pure rubber, were generally covered to the same thickness only as the small wires.

For these larger cables, therefore, a different method of preparing and applying the rubber was introduced, which allowed of a much thicker covering being put on than was possible, at the same cost, with pure rubber, besides bringing with it other advantages of considerable importance. For this purpose the rubber was thoroughly mixed and kneaded together with pigments such as litharge, French chalk, oxide of zinc, barytes, lamp black, sulphide of lime, etc.; which, although generally lowering the specific insulation resistance, produced a compound rubber a good deal cheaper, volume for volume, than the pure rubber, and one which was stronger mechanically and less liable to decompose, when the rubber and pigments were carefully chosen so as to suit one another, and were thoroughly well mixed. Some of these pigments, especially litharge and French chalk, have a drying effect, and [illegible] hinder decomposition by absorbing the solvent which is the active agent; whilst others make the compound tougher or harder. The pigments to be used, and the

quantities of each, must therefore be determined with special reference to the quality of the rubber, and the conditions under which it is to be used. The mixed rubber is run out into sheets and cut into strips of suitable width, which are applied to the conductor under considerable pressure, and in such a manner that two longitudinal joints are formed along the whole length, where the strips of rubber are squeezed together. Although these joints are only mechanical, yet if the rubber is in good condition and the edges clean, they are sufficiently good to permit of the cable being used under water. Before being covered with rubber, the conductor is usually wrapped with a prepared tape, and outside the rubber another tape is placed, and the whole is then covered with a strong braiding, and coated with a compound to keep the fibrous covering from rotting.

The advantages of the compound, over the pure rubber, insulation are that the former makes a practically homogeneous and waterproof covering, which, owing to its greater thickness and strength, will bear rougher handling without injury; and that the compound rubber does not decompose so rapidly, and is affected to a lesser degree by variations of temperature. Cables insulated in this manner have been in use for some years, not only for internal wiring, but also for outdoor work, both overhead and underground, and on circuits working in many instances with high pressures. These cables have given satisfactory results, although in some cases the mechanical joint between the two strips has been a cause of trouble; but the rubber, superior as it is in lasting qualities to the pure strip, is still not in the state in which it is most durable and least affected by variations of temperature.

The class of rubber cable which is most used at the

present time, is that in which the rubber is vulcanized; and its use in this form, in preference to any other, is justified, not only by the experience already gained with electric cables, but by the fact that almost all manufactured rubber articles are treated in this manner; and that when durability, flexibility, and the capability of withstanding high temperatures are required, the experience of rubber manufacturers has shown them that vulcanized rubber is the best, and indeed only, form of rubber which is thoroughly satisfactory. The process of vulcanization, or curing, is performed by mixing with the rubber a small quantity of sulphur, and by subjecting the mixture to a temperature of from 250° to 300° Fahr. whilst keeping it under pressure. The actual percentage of sulphur required, the temperature, and the length of time during which it is maintained, vary very much with the quality of the rubber used; some rubbers allowing only of a small variation of temperature, whilst others may be vulcanized by being subjected to a temperature as low as 250° or as high as 300°, the time varying perhaps from four or five hours to under one hour. It is therefore very necessary, when vulcanizing joints for instance, that full directions, as to the best temperature and time during which it is to be maintained, should be got from the manufacturer for the particular quality of rubber in use, and also that the permissible limits of variation of temperature and time should be defined, as otherwise there is a risk of either undercuring the rubber, or overcuring or burning it.

By this process of vulcanization the sulphur is made to combine chemically with the rubber, with the result that the action of the decomposing agent is neutralized, and the durability of the rubber immensely increased; and at the same time it is made mechani-

cally stronger, more flexible, and capable of withstanding a higher temperature without injury. The joint between two pieces of rubber, when they have been vulcanized together, is also no longer a mechanical one, but the two pieces are completely joined together into one homogeneous mass, so much so, indeed, that it is not possible by examination to discover the exact position of the joint. The use of sulphur has been objected to by some people on account of its deteriorating effects on the copper wire, but this difficulty may be overcome by tinning the copper wire, and by a proper proportioning of the quantity of sulphur used; that is, by mixing only just so much as will combine chemically with the rubber, so that little or no free sulphur is left which may act on the wire.

A method frequently employed to prevent this action, is to interpose a coat of specially mixed rubber, called technically the separator, between the sulphurized rubber and the conductor; the function of the separator being to combine with any excess of sulphur, and so prevent it from passing through to the copper. One of the early methods, proposed by Hooper for using vulcanized rubber as an insulator, consisted in first covering the conductor with pure rubber, then putting on a thin metal covering, and over this the vulcanizing rubber; but in the cables actually made by him, the metal covering was replaced by a layer of rubber highly pigmented with oxide of zinc, and this form of separator continues to be extensively used at the present time. There is, however, very little need for the use of a special separator, which is often inferior in mechanical and electrical qualities to the vulcanized rubber proper; since the right amount of sulphur can be so nearly determined, that the quantity of it left free, after vulcanizing, may be made infinitesimally

small, and its action on the wire, if any, may be reduced to a slight tarnishing of the exterior surface.

The method of insulating the conductor, which is most generally adopted at the present time, is to first wrap round it one or more layers of pure rubber tape, which are put on spirally; the direction of the spiral being reversed for each successive layer. On the top of this the compound rubber is applied in two or more separate coatings, each coat being put on by passing the partially formed core with two strips of compound rubber, one above and one below it, between a pair of rollers, which fold each strip half round the core, and firmly press together the edges of the upper and lower strips in such a manner as to make a good longitudinal joint along each side. When a sufficient number of layers of compound rubber has been put on to give the requisite thickness, the core is tightly bound with a spiral wrapping of prepared rubber tape, and is then ready for vulcanizing. The object of putting the compound rubber on in several separate layers is, to render it practically impossible for any weak place in the rubber to extend right through the covering; as, if we suppose that in any given length there is one faulty place in each coating, it is extremely improbable that they should all occur at the same point. Another reason is, that the longitudinal joints are better made with a number of comparatively thin layers, and the soundness of these joints is, as will be readily understood, most important. In order that the several layers, as many as eight or ten being put on some heavily insulated cables, should adhere together, and that the longitudinal seams should be well made, it is necessary that the surfaces of the rubber should be absolutely clean and free from grease of any kind; and the successful manufacture of these cables depends, to a very

great extent, therefore, on the careful handling of the rubber.

The pure rubber may be replaced by a layer of prepared tape, which very effectively keeps the copper clean, although it does not add to the resistance like the pure rubber; and, of the coatings of compound rubber, some may be of a separator, and some of a sulphurized rubber, or all may be of one quality. When ready for vulcanizing, the core is coiled on drums which are put into a steam chest; or, for larger sizes which cannot conveniently be so treated, the core is coiled in layers in large iron tanks, the layers being supported, and separated from one another, by being embedded in chalk or other similar material. The core is then kept at the proper temperature for such a time as is best suited to the particular quality of rubber which has been used. When taken from the cure, the core should be immersed in water, and tested for insulation resistance, to see that there are no faults in the covering, and that the resistance is up to the proper standard for the quality of rubber that has been employed; and, if satisfactory, it is then taken to the taping or braiding machines, where the external covering of compounded tapes or braiding is put on.

Although a covering of lead is in no way necessary for insulating purposes with a waterproof material like rubber, these cables are sometimes encased with lead as a further mechanical protection. This may be done by drawing the cable into a lead tube, which is afterwards drawn down through dies, until it fits tightly on the cable; or the lead covering may be put on in a hydraulic press in the manner usually adopted for covering the fibrous insulated cables. When laid in the ground direct, instead of in a pipe or conduit, these cables are sheathed with galvanized iron wires, or

with iron tapes laid on spirally in two reverse laid layers.

The methods employed to reinsulate the conductor at places where joints have been made, affect the satisfactory working of the cables and wires to a considerable extent; and of the two methods to be described, the second, in which the rubber is vulcanized, is vastly superior to the first, and should always be used for outdoor work, and on high pressure circuits. The first method, by which the joint is insulated with pure rubber, gives, however, sufficiently good results for all practical purposes, when low pressures are used, and

FIG. 32.

the joint is not exposed to high temperatures or much moisture; and, owing to its greater simplicity and cheapness, it is universally used for indoor work.

PURE RUBBER JOINT. The copper joint having been made in the manner described on p. 97, and left with a smooth and clean surface, the external tapes and braidings should be stripped back from the rubber, so as to be well clear of the part to be covered with the new insulating material; and the surfaces of the old rubber, which have been exposed during the making of the copper joint, should be cut away, and the rubber, if of sufficient thickness, trimmed down to a long bevel (*see* Fig. 32). The bare part of the conductor, and the

bevelled surfaces of the old rubber should then be lapped tightly and evenly with pure rubber strip, until the diameter becomes equal to, or slightly greater than that of the original core. Strong prepared tapes should then be lapped tightly over the rubber, and, for a short distance, over the original braiding, and the whole well varnished. India-rubber solution is often used to make the adjacent strips of pure rubber adhere to one another; but this is generally unnecessary, if the rubber is clean and is put on with enough tension; in any case the solution should be used very sparingly, and ample time should be allowed for the spirit to evaporate before it is covered by another layer of rubber. The plan of smearing each layer with a quantity of solution, and immediately covering it up with rubber, is one of the surest that can be devised for speedily rotting the rubber. When the thickness of rubber is not sufficient to allow of its being trimmed to a bevel, the pure rubber may be lapped over the outside of the old rubber for say an inch at each end; the surface of the old rubber being first scraped with a knife, and then wiped with pure benzole to free it from grease or dirt.

Vulcanized Rubber Joint. In addition to the tools required for pure rubber joints, the making of a vulcanized joint requires apparatus for maintaining it at a high temperature for a given length of time; and this apparatus must be fairly portable, and must not take up too much space, since it has often to be used in joint boxes of very moderate dimensions. In the factory the rubber is cured by being kept in contact with steam, but the difficulties of arranging a sufficiently portable steam plant have led to the use of a bath of molten sulphur, in which the joint is placed. This bath or cure may consist of a split

T-box (Fig. 33), the two halves of which are flanged, and can be bolted together, having three openings, one at each end and one at one side. The bottom half of the box is provided with a tap, and the top half with a hole through which the sulphur can be introduced; and in which a thermometer can be placed, so that the bulb is in the molten sulphur, whilst the scale projects outside the box. The temperature is maintained by placing one

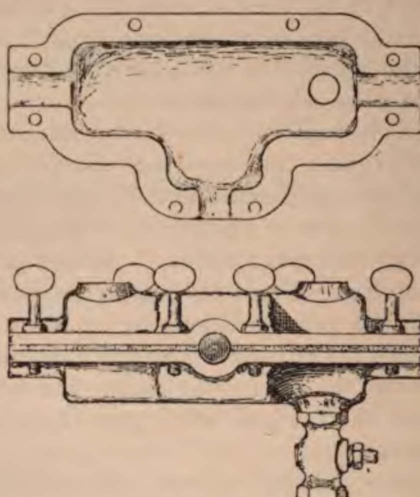

FIG. 33.

or more spirit lamps under the cure, and a pot is provided, in which the sulphur is melted over the firepot used for heating the soldering irons.

The joint is prepared for insulating in the manner already described, and as the cleanness of the bevelled surfaces of the rubber is of the utmost importance, they should be well scraped, and then wiped with pure benzole to free them from dirt or grease. One or more layers of pure rubber are first lapped tightly

round the conductor, and arranged so as just to overlap the inner edges of the old rubber; then, over this and the bevelled surface of the rubber, are lapped layers of vulcanizing rubber, until the diameter of the joint is about equal to that of the original core. The rubber should be put on tightly and evenly, so as to leave no spaces filled with air, and the joint should first be covered with a prepared tape put on spirally, then with a piece of sheeting firmly rolled round it so as to make a longitudinal seam, and finally, it should be tightly bound up with strong selvedge tape applied spirally. The sheeting and selvedge tape are put on to act as a mould, and keep the joint in shape and under pressure, whilst it is being cured, and they are removed again as soon as the vulcanization is completed. The bottom half of the cure is then placed under the cable, so that the joint is wholly within it: the cable is wrapped with common rubber, where it passes through the openings in the cure, so as to protect the original insulation from overheating, and to make tight joints at the openings; the top half of the cure is bolted on, and the molten sulphur poured in. It is advisable to warm the cure before fixing it on the joint, so that the sulphur may not be too much reduced in temperature by the mass of iron in the cure box, as otherwise, it may be difficult to raise the sulphur to the right temperature without a considerable loss of time; and with some rubbers this may cause trouble, owing to the uncertainty which thus arises, as to the proper time to keep them at the full temperature. According to the instructions issued by the Silvertown Company, the rubber they supply for vulcanized joints must be maintained at a temperature between 280° and 300° Fahr. for half an hour at the upper limit, or three-quarters of an hour

at the lower limit, intermediate times being allowed for temperatures between these two; but, if possible, the temperature should always be kept between 290° and 300° Fahr.

At the expiration of the proper time, the molten sulphur is run out through the tap in the bottom of the cure, the cure removed, and the wrappings of selvedge tape and sheeting stripped off. A convenient test of the degree of vulcanization is to try and indent the rubber, when cool, with the thumb nail; if it is properly cured, it will yield to the pressure, but no mark will remain; if the imprint of the nail is left, the rubber is not sufficiently cured; and if it feels hard and unyielding, it is probably overcured. The vulcanized joint is protected externally by lapping it with strong tapes, which should extend an inch or so over the braiding of the cable, and should be well varnished.

Although the best qualities of rubber cables give most excellent results, it must always be remembered that the rubbers used are in most cases mixtures; and that, therefore, there may be a very great difference between two cables, both of which are insulated with rubber compounds. For instance, as regards specific resistance, some compounds give ten or more times the resistance of others; and, although there is no absolute rule, it is generally found that the rubber which gives the higher resistance is also that which is the more durable. For this reason it is often necessary to use a cable giving a much higher insulation resistance than is absolutely required for the work, in order that it shall be made of a good quality of rubber, and of sufficient thickness to withstand the mechanical strains to which it may be subjected. Besides those compounds which usually go by the name of rubber, there are others, such as okonite, which are also mixtures

of rubber; the special name denoting rather a difference in the process of manufacture than in the material used, as this is varied according to the requirements of each type of cable. One of the leading features in the manufacture of okonite cables, to which great importance is attached in the patent specifications, is the different method of applying the covering; the strip of okonite being laid on a strip of tin foil, and both folded around the wire so that there is only one longitudinal seam; the core also being left enclosed in the tin foil, which is only removed after the okonite has been vulcanized.

Gutta percha, which is so largely used for submarine cable cores and underground telegraph lines, is an insulating material which has met with very little favour for electric light cables, on account of the low temperature at which it softens. The process of manufacture consists in passing the wire to be covered, first through a bath of Chatterton's compound, and then through a press containing gutta percha maintained in a viscous state by the application of heat; the gutta percha being forced out around the wire, as the latter passes out through a die. The covered wire is then led through troughs of cold water to set the gutta percha, and is coiled on a drum, and taken to be examined; during which process any faulty places in the covering, that may be discovered, are put right by hand. The core is then taken back to the machine, and another coating of gutta percha is put on; and this process is repeated again and again according to the number of coatings required on the wire. The covered wire may then be taped, or drawn into lead tubes, or it may be served with jute and armoured, according to the nature of the mechanical protection which is required.

Joints are insulated in the following manner: The gutta percha is pared back for a couple of inches or so, to remove its outer surface, the wire is covered with Chatterton's compound, and the gutta percha heated on both sides of the joint, and tapered down over it so as to entirely cover the wire. A coating of Chatterton's compound is then put on, and a sheet of gutta percha, previously warmed, is laid over and pressed tightly round the joint, and the excess trimmed off with a pair of scissors. The seam is pressed up tight and finished off with a warm tool, which is worked in such a manner as to mix the gutta percha on both sides of the seam into a homogeneous mass. When cool, the joint is covered with compound, and another sheet of gutta percha is put on and finished off in the same way; and this process may be repeated according to the thickness of the insulating covering.

Bitite, which is the insulating material used by the Callender Company, is said to be bitumen absolutely refined to purity, and vulcanized. The conductor is covered with a solid sheath of this material, put on in one operation under pressure, and is served with a tape; then covered with insulating compound and again taped, then braided with hemp yarn, and passed through a bath of hot asphalte compound.

Joints in these cables are insulated by wrapping the conductor with bitite, which has been half vulcanized, up to the diameter of the original insulation, and then protecting it by a wrapping of compounded tapes. The joint is then heated by means of a lamp to make the wrappings solid, and to complete the vulcanization of the bitite. Very often, however, mechanical joints are made in special boxes. These boxes have double walls (Fig. 34), through which the cables are passed into the inner box, where the connections are made by means

of copper bridges. The space between the inner and outer box, and sometimes the inner box itself, is then

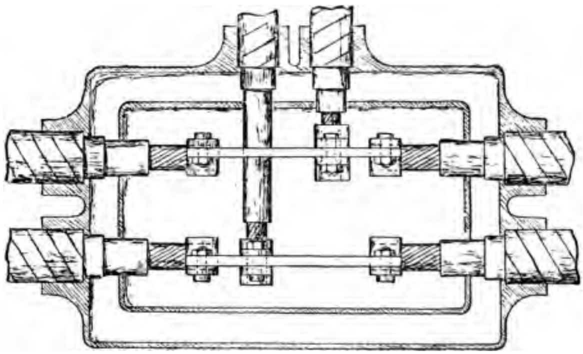

FIG. 34.

filled up with bitumen, to prevent moisture from getting into the joints, and the box is covered in.

CHAPTER X.

Lead-covered Cables.—Early patents.—Methods of Putting on Lead Covering.—Cable Terminals and Joints.—Terminal Boxes.—Joint Boxes.—Edison Tube and Joint Boxes.—Ferranti Concentric Main and Joint.—Brooks' System of Oil Insulation.

THE continuously insulated cables, which have been described in the preceding chapter, although sometimes encased in lead, are not dependent on that covering for the maintenance of their insulation; but there is a type of cable which has been employed a great deal in the last few years, in which the lead covering is not only a mechanical protection, but an integral part of the insulating coating; since it is depended on for the exclusion of moisture from the wrapping of impregnated fibrous material, with which the conductor is surrounded. This type of cable is often spoken of as though it were an invention of recent date, but in reality it was one of the earliest to be tried; indeed, one may say it was the earliest form of cable that showed any signs of being a success. It will be remembered that the first underground wires were insulated with cotton steeped in a resinous compound, and that it was found impossible to keep the lines in working order, owing to damp penetrating through the cotton covering. The immediate result of this was the replacing, wherever possible, of the underground lines by bare wires fixed on insulators overhead; but many of the early workers were strongly impressed with the advantages of an underground wire, and continued, therefore, to search after some

method of overcoming the difficulties which had caused the first lines of this kind to be abandoned.

The outcome of their labours is given in two patent specifications dated 1845, and in a third in the following year, each of which described methods of enclosing the fibrous material in a casing of lead. The first, that of Wheatstone and Cooke, proposed that sheet lead should be folded round the cotton covering, and a longitudinal soldered joint made; or, as an alternative, that the lead should be moulded round the covered wire by hydraulic pressure, in the well-known manner of making lead tubes from semi-molten metal. The second, that of Young and McNair, proposed that the conductor, covered with cotton, should be drawn through a vessel containing the hot compound with which it was to be impregnated; and from this vessel through a tube, which passed into a cylinder containing lead at a temperature between 250° and 400° Fahr., and which terminated in a nozzle abutting against the die, through which the lead was forced out around the wire by hydraulic pressure. The third, that of Mapple, described a process in which the fibrous-covered conductor was drawn into a manufactured lead tube, which was afterwards drawn down by passing through rollers or dies, until it fitted tightly around the covered wire. The methods proposed by these inventors resemble very closely those which are in use at the present time; and the fact that this type of cable did not come into general use is no doubt due to the introduction soon afterwards of gutta-percha-covered wires, which at once took the first place in the estimation of telegraph engineers, who found them, though far from perfect at that time, much superior to the fibrous cables.

Since the re-introduction of this type of cable, many

improvements have been made in the details of the manufacture, and much more attention paid to the drying of the fibrous material, and to its thorough impregnation with compound; and it is now employed very largely, more especially on the Continent and in America. The materials used by the different manufacturers are cotton, flax, jute, or paper, impregnated with paraffin, ozokerite, bituminous, or resinous compounds; the lead casing is put on in a press either at a high temperature with a moderate pressure, or at a low temperature with an increased pressure; or the covered conductor is passed into a lead tube, which is afterwards drawn down by dies till it fits tightly, or is filled by injecting insulating material into it until all spaces, not occupied by the covered conductor, are filled up. Since the object of using the lead casing is to enclose the fibrous material in a waterproof covering, it is of the utmost importance that the method employed should be one that will ensure, as much as possible, the absence of flaws in the lead, and that will allow of the condition of the casing being ascertained during manufacture; and, for this reason, the method adopted for enclosing the covered conductor is a more important distinguishing feature of any system than the particular kind of fibrous material or compound which is used.

The Berthoud Borel cable may be taken as an example of the high temperature process, the covered conductor being immersed in a bath of hot linseed oil and resin, from which it passes, when thoroughly impregnated, direct to the lead covering press; where the lead in a molten condition is forced out through a die, through the centre of which the core is passed. This lead-covered core is then wrapped with compounded tapes, and a second lead covering is put on

as an additional protection ; the object being the same as that with which such materials as rubber or gutta percha are put on in several distinct coats, namely, that any flaw in one covering may be protected by the other, which is not likely to be faulty also in exactly the same spot. From this point of view the second lead covering is a decided advantage, but it greatly increases the weight and bulk of the cable, and decreases its flexibility ; and the fact that the makers have found it necessary to duplicate the lead covering, and thereby incur these disadvantages, appears to confirm the opinion that the lead is more porous, and less even in thickness, when put on at a high temperature, than it is when a greater pressure is used, and the temperature is lower.

The Siemens, Felten and Guilleaume, Fowler Waring, Callender, and Silvertown lead-covered cables are all examples of the low temperature process; and it is claimed for these cables that the lead covering, which is put on under very considerable pressure, and at a temperature which is well below its melting point, is stronger, less porous, and more uniform in thickness, than when a higher temperature is maintained. In the Siemens cable the conductor is wrapped with jute and impregnated with a special bituminous compound mixed with a heavy oil, and is then covered with lead. Over the lead is laid a covering of strong compounded tapes or jute, and on that two reverse-laid spiral wrappings of iron strip, and the whole cable is then served with compounded jute. The other cables mentioned above are made in much the same way, either armoured or unarmoured according to requirements, the compound used being generally a bituminous or resinous mixture.

Another lead-covered cable of this class, which has

recently been introduced, is that made by the Norwich Insulated Wire Company of New York, who use paper instead of cotton or jute, as the material to be impregnated. The paper is wound on in strips spirally over the conductor, and as each spiral is laid on, it is passed through a die which presses it into a compact mass. The core is then exposed to a temperature of about 250° Fahr. to expel the moisture from the paper, and is immersed in a bath of special compound from which it passes direct to the lead-covering press.

With either of the methods of lead covering by a press, it is difficult to test the soundness of the lead, unless the cable is immersed for a very long time in water; and a partial flaw may easily exist, which, even after long immersion, will not allow moisture to get into the fibrous covering, but will, perhaps, develop into a complete fault after the cable has been coiled or uncoiled on drums, or in any other way been subjected to bending strains.

For this reason some makers have preferred to use the manufactured lead tube, which can be tested under pressure to see that it is sound, and to draw into it the covered conductor. The plan of drawing down the tube with dies is seldom used, as it leaves the fibrous covering exposed during the process, and it is consequently impossible to obtain a good insulation resistance owing to the absorption of moisture; but this difficulty may be avoided by filling up the space between the covered conductor and the tube with insulating material, instead of reducing the diameter of the tube preelf. A good example of this class is the Patterson the le, in which the conductor is wrapped with cotton a die, thnregnated with paraffin; it is then drawn into This lead-c, through which aerated paraffin is pumped pounded tapeere. The act of filling is therefore a test

of the soundness of the tube and joints, as the pressure is sufficient to force the paraffin out through any weak places. The admixture of dry gas with the paraffin is made to render it more elastic, and also to reduce the electrostatic capacity of the cables; and it is claimed by the makers that the natural shrinkage of the paraffin, which is a great objection to its use, is compensated for by the expansion of the gas, and that the formation of cracks, through which moisture might penetrate in case of damage to the lead pipe, is prevented, and any fault caused by such an accident is therefore kept from spreading along the cable.

The readiness with which all fibrous materials absorb moisture makes it necessary to take special precautions for insulating terminal connections, and renders the liability to a decrease of insulation, wherever a joint is made, greater than with cables covered with a waterproof material. To overcome this difficulty, special cable terminals and joint boxes have been devised by the manufacturers of lead-covered cables, the former being used when connection is made to switchboards or other apparatus, and the latter when it is not convenient to make a lead-covered joint in the cable. If these special apparatus are not used, a joint is insulated by wrapping it with prepared tapes, great care being necessary to keep the exposed insulating material free from moisture; and over this wrapping a sleeve of lead is placed, which is fixed to the lead covering on either side by wiped solder joints. Sometimes the lead sleeve has a hole made in it near its centre, through which insulating compound is forced to fill up any spaces, and make the joint solid, the hole being soldered up afterwards so as to make all tight. When the conductor has to be bared to make connection to any apparatus in the circuit, the lead is cut back a

little way, and the exposed fibrous material dried by the application of heat: it is then tightly wrapped with rubber strip which extends a little way over the bare conductor at one end, and over the lead tube at the other end, so as to exclude moisture as much as possible from the insulating material.

The terminal and joint boxes used by different manufacturers are all much the same in principle, the idea in all of them being to enclose the exposed in-

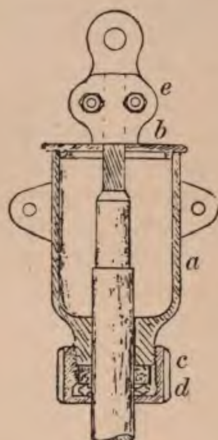

FIG. 35.

sulating fibre in a watertight box, filled with a heavy oil or other insulating compound.

The following illustrations of the apparatus used by Messrs. Felten and Guilleaume in connection with their lead-covered cables, will show very clearly the general plan which is adopted for this purpose. The box for terminating an ordinary single cable is shown in Fig. 35, in which *a* is a metal case, closed at the top with an ebonite cover *b*, and terminating at its lower end in

a gland with a rubber washer *c* and nut *d*. The method of preparing the cable is to cut off the insulation for several inches, and the lead tube for 2 or 3 inches more, leaving the fibrous material exposed. The end of the conductor is cleaned and tinned, and the fibrous covering trimmed down to a short taper; the nut, washer and case are then passed over the end of the cable and fixed in position on it, a tight

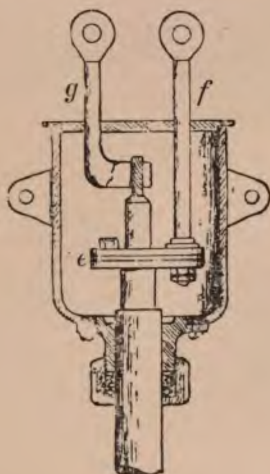

FIG. 36.

joint being made by screwing up the nut. The case is filled up with insulating material, which must be continually added so long as there are any signs of its sinking in level, and is then closed with the ebonite cover; and finally the projecting end of the conductor is screwed up tightly in the clamp *e*.

A similar box is used for terminating a concentric cable, the end of which is prepared by cutting off the lead tube for several inches, then cutting away the

outer insulating fibre to within an inch or two of the lead tube, and bending out the wires of the outer conductor at right angles to the cable, thus exposing the inner fibrous covering (see Fig. 36). This inner covering is then partially removed, so as to leave bare the end of the inner conductor as shown. The wires of the outer

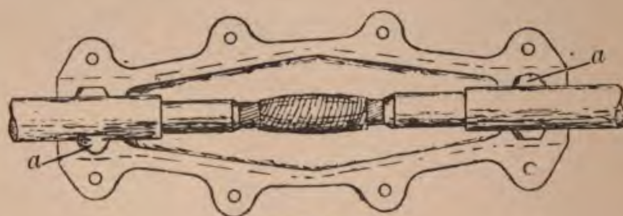

FIG. 37.

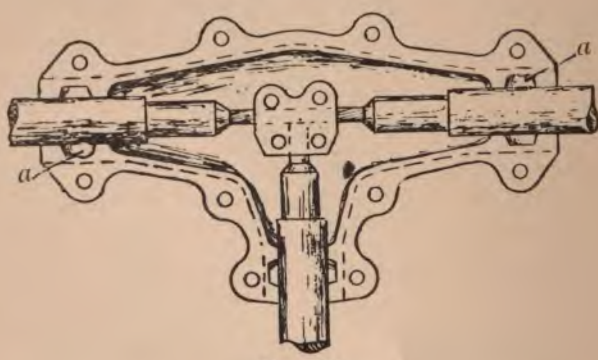

FIG. 38.

conductor are clamped between two metal plates *e*, to which is connected a gun-metal rod *f*; and the inner conductor is soldered or clamped to a bent rod *g*. The case is filled up as before with insulating material, and closed with an ebonite cover in two pieces.

For making straight or T-joints in the cable a clamp may be used, or the copper joints may be soldered in

the usual way; the joint in either case being enclosed in a box made in two halves, which are bolted together. Fig. 37 shows a soldered straight joint, and Fig. 38 a T-joint made with clamps. The ends of the cable are prepared in the manner already described, and the conductors soldered or clamped together; the lead tube being cut off, so that about $1\frac{1}{4}$ inches or more of it will project inside the box. The bottom part of the box is then placed under the joint, and the upper part over it; the two halves being bolted together with india-rubber packing between them to make a tight joint. In the top half of the box holes are provided, one leading into the interior proper of the box, and one into each of the small chambers marked *a*. Through these holes the main box is filled with insulating material, and the small chambers with asphalte; the holes themselves being afterward closed with screw plugs. Fig. 39 is an elevation of a similar box arranged for making a straight joint in a concentric cable, and Fig. 40 a plan of a box containing a T-joint in a similar cable. The inner conductors are connected by a clamp similar to that used for the ordinary single cable; and the wires of the outer conductors are, as before, bent out at right angles, and clamped between two plates, these plates being connected by coupling bars as shown.

The insulated conductors, which have been described so far, are all of them made in the factory in the form of cables of considerable length, and must therefore, for convenience of handling, be more or less flexible; but there is another type of insulated conductor which is supplied in short rigid pieces, which are jointed together during the process of laying; the most prominent examples of this type being the Edison and Ferranti tubes. The method of construction adopted with these conductors permits of the use of solid rods.

or tubes of copper of considerable sectional area, in the place of wire strands; but it also entails the making of a joint in the conductor once every 20 feet or so,

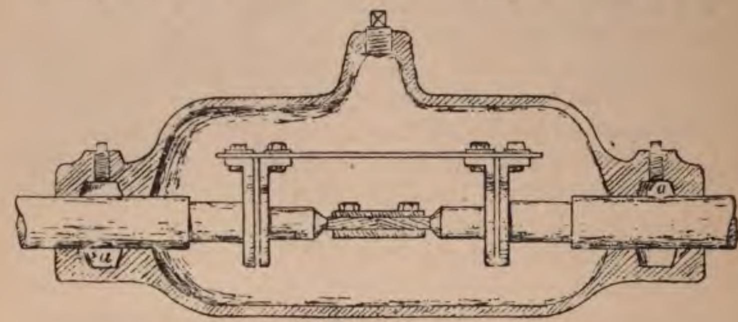

FIG. 39.

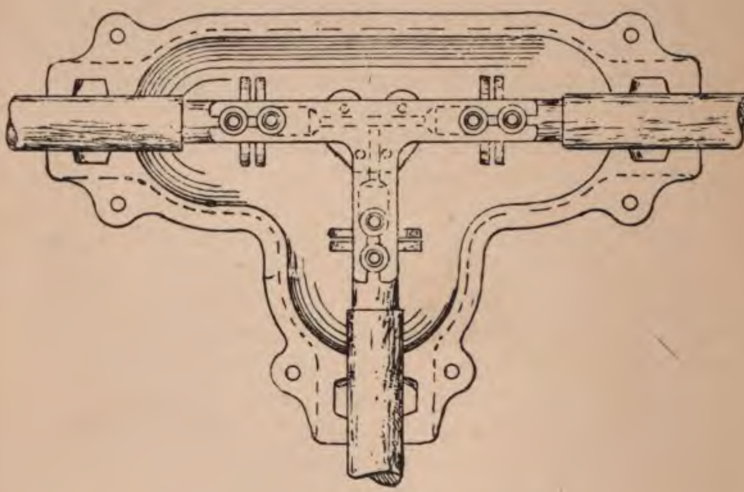

FIG. 40.

and therefore also a break in the continuity of the insulating covering.

The Edison system of underground mains was first

introduced about ten years ago, and was the first and, for a long time, the only system which could be fairly described as a complete one for dealing with the distribution of low-pressure currents by underground conductors. The details of construction of the tube have been modified in many respects from time to time; but, as at present made, the conductors, of which there are three, consist of solid copper rods about 20 feet long, which are spun over separately with dry string and then placed in position in the centre of a steel tube. The length of this tube is somewhat less than

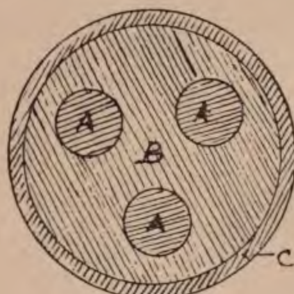

Fig. 41.

AAA.—Copper Rods.
B.—Insulating Compound.
C.—Steel Tube.

that of the copper rods, so that the latter project a few inches at each end. This tube is connected to a pump, by means of which a vacuum is first created, and then a hot bituminous compound drawn in to fill up all the space within the tube, which is not already occupied by the conductors. By this means a three-wire main, (shown in section in Fig. 41), with the conductors surrounded with insulating material, and protected mechanically by the containing tube, is turned out in sections of 20 feet or thereabouts; and in this form the

sections are delivered from the factory to be laid in the ground, the joining together of the lengths being performed when they are placed in position. The connections between the corresponding copper rods are made by means of short lengths of flexible copper cable, to each end of which are sweated lugs provided with holes for the copper rods to enter (Fig. 42). A

FIG. 42.

split cap (Fig. 43), which forms part of a ball and socket joint, is then bolted to the end of each tube, and these caps are fitted into sockets prepared in the

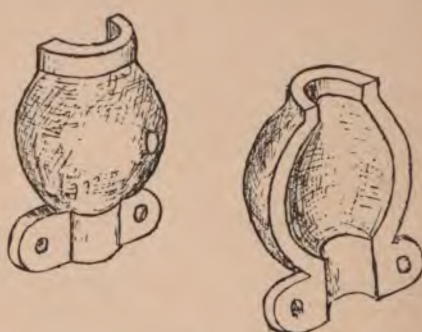

FIG. 43.

outlets of a split cast-iron box, the two halves of which are bolted together, so as to hold the caps, and therefore the tubes, firmly. The ball and socket joints allow of a limited deviation from a straight line in the alignment of the tubes, and give sufficient flexibility for the requirements of laying them in position under the

roads. The upper half of the cast-iron box is provided with a couple of holes, which can be closed by screw plugs, and which are used for filling in the box with a hot bituminous compound. For straight joints a box with an opening at each end is used (Fig. 44), and for T-joints one with three openings, as shown in Fig. 45, which also shows the method of connecting the main and branch cables.

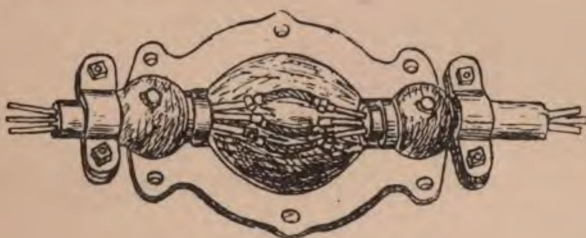

FIG. 44.

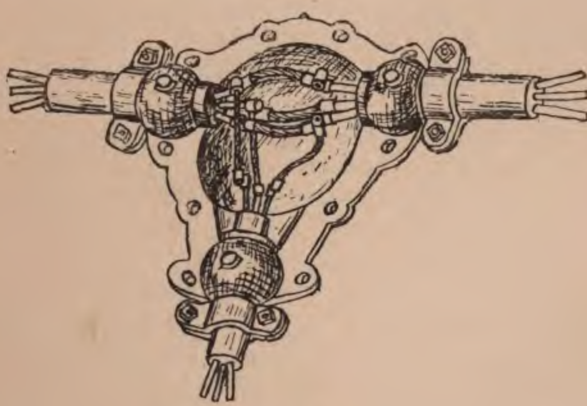

FIG. 45.

The Edison system has had a very extended use in America, where a large mileage has been placed under-

ground, and on the whole has given satisfactory results; although it has been by no means free from trouble as regards insulation. For distributing mains, the joint box every 20 feet is convenient, as it affords great facilities for branching off service wires; but the number of these boxes, and the difficulty of keeping them all watertight, is not conducive to high insulation resistance. The localizing and removal of a fault also necessitates the digging up of the conductor, and this opening up of the ground may become a serious item of expenditure, unless faults are of very rare occurrence. This system is used by most of the local Edison Companies in America, though this is not universal, as several of them are now using cables, as also is the Continental Edison Company in some of its installations in Paris and elsewhere.

The Ferranti mains, which connect the London Electric Company's station at Deptford with the distributing stations in London, are also made in short rigid lengths, delivered from the factory with their ends prepared for jointing; the joints themselves being made as the main is laid in the ground. This main, which is concentric, consists of two tubes of copper, one entirely within the other: the inner and outer tubes are insulated from one another by brown paper steeped in black wax, the outer tube is covered with the same insulating material, and the whole protected from mechanical injury by being enclosed in an iron tube (Fig 46). The inner tube of copper is about 20 feet long, $\frac{9}{16}$ths of an inch internal diameter, and $\frac{13}{16}$ths of an inch external diameter, and on it are wound layers of the prepared brown paper, of a width equal to the length of the tube, until the diameter is increased to $1\frac{27}{32}$nds of an inch. The insulated tube is then placed inside another copper tube, whose diameter is a little larger than that of the paper

insulation; and the outer tube is drawn down through a drawplate until it fits tightly over the insulation. The external diameter of the outer tube is $1\frac{15}{16}$ths of an inch; and on it is wound brown paper, steeped as before in a bath of hot wax, to a thickness of $\frac{1}{8}$th of an inch, and the whole is then placed inside an iron tube about $\frac{1}{16}$th of an inch thick. This tube is provided with a hole through which hot wax is forced by a pump, so as to drive out the air, and make a solid mass of

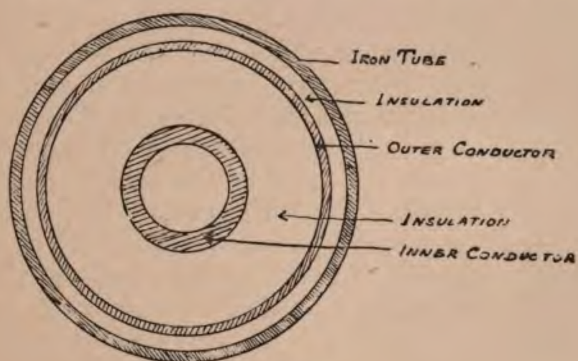

FIG. 46.

insulating material between the outer copper tube and the iron tube.

Each length of the main is then taken to a hollow spindle lathe to have its ends prepared for jointing, which is done in the following manner:—At one end a length of 17 inches is cut off the iron tube; the outer insulation, which is left exposed, is removed for a distance of 14 inches from the end; a length of 6 inches is cut off the outer copper tube; the inner insulation is turned so as to form a male cone, extending from the end of the outer copper tube to the end of the inner one; and finally the inside of the inner tube is

FIG. 47.

rymered out for a length of 9 inches, so as to provide a truly cylindrical hole of the exact size required. At the other end a length of 11 inches is cut off the iron tube, and 8 inches off the outer insulation; the insulation between the two conductors is then turned, so as to form a female cone 6 inches long, which exactly corresponds with the male cone at the other end; and the inside of the inner tube is rymered out. A solid copper rod 18 inches long is driven into the inner tube for a distance equal to half its length, and a sleeve of copper 16 inches long is pushed over the outer copper tube, so that it encloses the 8 inches from which the outer insulation has been removed. This sleeve is firmly fixed in place by means of a tool, with which three or more circular corrugations are made, so as to indent both the sleeve and the outer copper tube. The tubes are now ready for laying, the joint (Fig. 47) being completed on the spot, by fitting the female end of one tube, with its projecting copper rod and sleeve, to the male end of another tube. The two tubes are drawn tight together by a screw press, whilst heat is applied to the joint to make the two coned surfaces of the insulation adhere to another; and the copper sleeve is fixed to the outer tube of the second length by means of circular corrugations made as already described. Before bringing the two ends together, an iron sleeve about 30 inches long is slipped on to one length; this sleeve at each end

nearly fits the protective tube, but is elsewhere somewhat larger in diameter; and in the enlarged part there is placed a sleeve of prepared paper. When the copper joint is completed, it is wrapped with insulation until the diameter is equal to that of the protected tube; the iron sleeve is pushed along so that it encloses the joint; hot wax is forced in through a hole in the sleeve to drive out the air, and fill up all spaces not already occupied by insulating material; the ends of the sleeve are fixed by circular corrugations, and the hole, through which the wax was introduced, is closed by a screw plug. Considerable difficulty was experienced at first in the making of these joints, owing to the system being an entirely new departure; but, when the men had been trained for a time and had got used to the work, the results were more satisfactory and the joints were made much better and more quickly.

Although the copper joints depend entirely on the surface contact due to the rod and sleeve making a tight fit with their respective tubes, the actual measured resistance of a main (which is 2·1 ohms for about 11,000 yards of double conductor) agrees very closely with the resistance as calculated from the sectional areas of the conductors; and this result is no doubt due to the large surface in contact at the joints, and the increased sectional area given by the rods and sleeves at these junctions. Dr. Fleming, in a paper on "Some effects of alternating current flow in circuits having capacity and self-induction," read before the Institution of Electrical Engineers, gave the following figures as the results of measurements made by him on a section of the main about 2,400 yards in length, the temperature being 32° Fahr.:—

Copper resistance, ·324 legal ohm per mile of double conductor.

Insulation resistance, 720 megohms per mile between inner and outer conductor.

Electrostatic capacity, ·367 microfarad per mile between inner and outer conductor.

From these figures it will be seen that the specific resistance of the insulating material is not very high, the ratio of outer to inner diameter of the insulation being about 2·3; but this is of little moment compared with its power of resisting disruptive discharge; as the resistance, which works out to 115 megohms for 11,000 yards, even if reduced by 50 per cent. by the temperature correction, is sufficient, if only it can be maintained constant under all conditions. The mains when laid were tested under a pressure of 20,000 volts, and with the exception of certain faulty joints, withstood the pressure; and since early in February, 1891, they have been in use with a working pressure of 10,000 volts. As regards insulation and the resistance to disruptive discharge, the weak point of the main is the enormous number of joints, at each of which the paper is divided, and the continuity of the covering depends on the wax only; so that there is a serious risk that, through bending, unequal expansion or contraction, or continued vibration, these joints will become faulty, and break down under the continued strain of the high pressure.

Another method of effecting the continuous insulation of a conductor, is that known as the Brooks oil insulation system; and here again the complete insulated cable is not made in the factory, but part of the work of insulating the conductor is done when it is in place. The conductor is braided with jute or hemp, which serves to keep it from mechanical contact with the pipe in which it is placed, or with any other conductor in the same pipe; and the insulation is

effected by filling this pipe completely with a fluid insulating material. At first an ordinary mineral oil was used for this purpose, but owing to the difficulties arising from the leakage of this oil from the pipes, it has been replaced by a heavy oil of a resinous nature, which has the consistency of a very thick treacle, and has not therefore the same power of penetrating through the joints in the pipe. This oil is said to have a high insulation resistance, to resist disruptive discharge very effectively, and to be of a permanent character, as it does not become oxidized when exposed to the air.

The iron pipes, in which the jute-covered conductor and the oil are contained, are laid underground, and provided with drawing-in boxes, and junction boxes according to requirement; and, at the highest point in the line of pipe, a cast-iron tank with removable cover is fixed, which serves as an oil reservoir, and ensures the pipes being kept full of oil so long as it itself is kept charged. The inlets to the boxes through which the cables pass are generally provided with glands, by means of which a tight joint can be made; thus allowing the oil to be withdrawn from the box for testing purposes, or for connecting up a branch, without at the same time emptying the pipes. When the pipes and boxes have been laid and all joints in the same made tight, the cables are drawn in. To prepare them for this stage, the braided cables, which are brought from the factory on drums, are placed in a portable tank containing fluid insulating material, and are maintained therein, at a temperature of about 300° Fahr., for a sufficient length of time to expel the moisture from the fibrous covering. They are then drawn into the iron pipes, into which the insulating fluid is forced so as to fill up all spaces

not occupied by the braided conductors. To preserve the iron pipes from the action of the soil, they are often laid in wooden boxes which are filled up with hot pitch.

This system of insulation resembles in some respects those in which impregnated fibrous coverings are enclosed in lead pipes; but it is claimed for it that the iron pipe employed is less likely to be injured than a lead pipe, and that the insulating material, being in a fluid state, is free from the difficulties which are met with in the ordinary lead-covered cable, due to the compound not filling up any small cracks which may be caused by bending. On the other hand trouble may be caused by a leakage of oil, which is much increased when many branches are taken off the main cables, and this system therefore seems better adapted for use for feeders than for distributing mains.

CHAPTER XI.

Importance of Testing.—Mechanical Tests.—Electrical Tests.—Conductor Resistance.—Bridge Method.—Fall of Potential Method.—Localization of Faults.—Insulation Resistance.—Joint Testing.—Test for Resistance to Disruptive Strain.—Capacity.

A MATTER of the first importance, in connection with the manufacture of electric cables, is the tests to which they should be submitted; not only after completion, but also at different periods during the process of manufacture. These tests should be both mechanical and electrical, and should be made if possible under the actual conditions of the future working of the cable; but when, as is generally the case, it is impossible to exactly reproduce these conditions, the tests to which the cable is subjected should be rendered more severe, so as to allow of a fair margin of safety. The advantage of any test, which subjects the cable to a greater strain than that due to the normal working conditions, is that this increased strain is likely to break down any weak place which may exist; and which, although not bad enough to cause failure when the cable is new, may after continued use become a source of trouble. The particular test to which these remarks especially apply, is that of the insulation of the cable; and this test should always be made in water, and with a greater pressure than that which is to be used on the electric circuit, in which the cable will be connected. We have seen that the requirements, which have to be satisfied by an electric cable in order that it may be suitable for its work, are that the resistance of the conductor shall not exceed a definite

value depending on its length and sectional area, and on the conducting material employed; that the resistance of the insulating covering shall be high, and shall follow a determinate law depending on the same factors; that it shall be permanent, and not liable to be diminished excessively by exposure to fairly high temperatures, and that any such decrease of resistance shall be temporary, that is that it shall last only so long as the high temperature is maintained; that the resistance shall not be impaired by damp; that the insulating material used shall be capable of withstanding without injury the disruptive strains due to a high electric pressure; and that the capacity of the cable shall be as small as possible. Besides possessing these qualities the cable should have considerable tensile strength, and the insulating and protective coverings should be such as will enable it to stand without injury the handling, to which it will be subjected after it leaves the factory.

Some of these necessary qualities, which practically come under the heading of durability, cannot very well be tested except by continued use, but much valuable information might be gained by subjecting samples to continued changes of temperature, in moist and dry air; by immersing them in such liquids and gases as are known to be sometimes present in the soil or in the atmosphere; by subjecting them to tensile and bending strains, and to high electrical pressures; and by testing them for insulation resistance at stated intervals during the period of trial. By trials of this kind, in which the conditions may be made much more exacting than those which are likely to occur in practice, results might be obtained after the lapse of a comparatively short time, which would give a very fair guide to the relative merits of different methods of insulating conductors.

Tests for mechanical strength can be made on cables before delivery, such as the test for breaking strain, or the wrapping of the cable round a bar of small diameter; and tests of this nature, though seldom made, would often be useful in checking the manufacture; for instance, a rubber-covered cable which had been over-vulcanized, would not stand the wrapping test so well, as it would be more liable to crack; or a lead-encased and fibre-insulated cable which had been exposed to too high a temperature, or to too long continued a heat in the drying and impregnating process, would also fail owing to the weakening effect of extreme heat on the fibre. In both these cases the cable might be passed, if it were only subjected to the usual electrical tests, and it would leave the factory with the chance of being easily damaged by the first rough usage it received.

The electrical tests which have usually to be made in the factory are those of the resistance of the conductor, the localization of faults, the resistance and capacity of the insulating covering, and, when the cables are to be used with high pressures, the resistance to breaking down or disruptive discharge; and the methods of conducting these tests will therefore be briefly described.

All these tests should be taken with the cable immersed in water, in which it should be allowed to remain for twenty-four hours or more, before any measurements are made; and care must be taken to maintain the water at a constant fixed temperature, so as to ensure that the tests are made under such conditions as will allow of a proper comparison of the results with the calculated data of the cable.

The resistance of the conductor may be measured by the Wheatstone bridge, a metre bridge being probably

the most convenient form, as the resistances are generally small; or by the fall of potential method, in which a current from a battery of accumulators is passed through the conductor in series with a standard resistance, and the difference of potential between the terminals of the conductor is balanced against that of this standard resistance. The first method is the one most usually employed, the connections for it being made as shown in Fig. 48. In the ordinary bridge resistance box the resistances R_1 and R_2 may be ad-

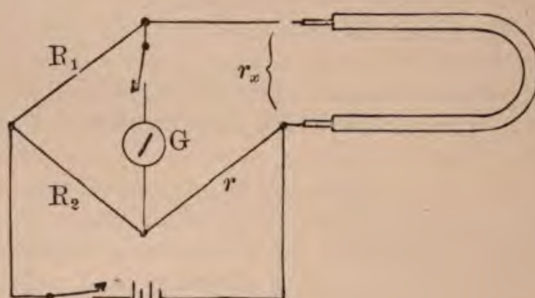

FIG. 48.

justed so that $\frac{R_1}{R_2}$ is any power of ten between 100 and ·01; whilst the resistance r can be adjusted by tenths of an ohm to any value between 9999·9 and ·1 ohm. The resistance r_x is given by the equation $r_x = r\frac{R_1}{R_2}$, and may be measured with fair accuracy if it is not less than one-tenth of an ohm.

For very low resistances the metre bridge is more convenient, that is, a bridge in which the resistances R_2 and r are replaced by a graduated wire, along which *a slider* connected to the galvanometer lead can be

moved, so as to make contact at any point along it. If, when equilibrium is obtained, the lengths of wire on either side of the galvanometer contact are respectively a and b units (see Fig. 49), then $r_x = R_1 \frac{b}{a}$. Great accuracy can be obtained by inserting resistance coils between the ends of the wire and the terminals to which the battery leads are attached; the effect being to virtually increase the length of the wire, so that each scale division becomes a smaller percentage of the total

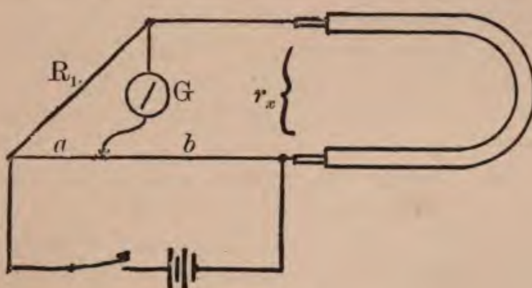

FIG. 49.

length. Of course the values of the added resistances must be known in terms of an equivalent length of the slide wire, and these values must be added to a and b in order that the equation given above may remain true.

With either of these arrangements of the bridge, two measurements have generally to be made, owing to the fact that the conductor under test cannot be connected direct to the bridge terminals; the first being the resistance of the conductor plus that of the wires connecting its ends to the bridge terminals, and the second the resistance of these wires or testing leads themselves. If, as is often the case, the distance from the cable tanks to the testing room is considerable, the

resistance of the testing leads may be greater than that of the conductor itself, and the possible degree of accuracy will then be much reduced. For example, suppose that the resistance of the conductor is x, and that of the testing leads y, the total resistance to be measured is $x+y$; then, if p is the percentage of accuracy that can be obtained, we can measure the resistance of $x+y$ correct within an amount equal to $\frac{p(x+y)}{100}$. This amount, however, is $p\frac{x+y}{x}$ per cent. of the resistance of the conductor; and therefore, if we suppose that we can measure a resistance accurately to one-tenth of one per cent., and that the resistance of the leads is five times that of the conductor, we cannot get this latter resistance nearer than six-tenths of one per cent.

For this reason, and also on account of the error introduced by the contact resistances when the leads are connected to the conductor or to one another, the second or fall of potential method is sometimes adopted for the measurement of very low resistances. To make this test, the conductor, whose resistance is to be measured, is connected in series with a standard resistance and a battery of accumulators, so that a current may be passed through the circuit. The standard resistance should be made of sufficient sectional area to carry the current without any appreciable rise in temperature; and it may be either a wire of fixed length and resistance, or a graduated wire like that used for the metre bridge, in which case one of the connecting wires is fitted with a sliding contact. One method of connecting up for this test is shown in Fig. 50, where R is the standard resistance, R_x the resistance to be measured, and r_1, r_2, r_3, and r_4 known resistances. When a balance is obtained, the following relation

between them holds good, viz. $\frac{R_x}{R}=\frac{r_3}{r_2}=\frac{r_4}{r_1}$. If a graduated wire is used for R, and the resistance r_1 connected to a slider, by means of which contact can be made at any point along R, then r_1, r_2, r_3, r_4 may all be fixed resistances, the value of R being adjusted till $\frac{R_x}{R}$ equals the ratio to which they have been set; but if R

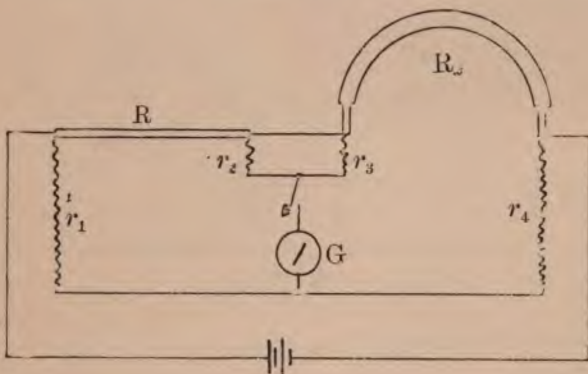

FIG. 50.

has a fixed value, then two of the other resistances, say r_3 and r_4, must be adjustable so that their values may be varied until $\frac{r_3}{r_2}$ and $\frac{r_4}{r_1}$ are each equal to $\frac{R_x}{R}$.

Another method is to use a differential galvanometer, the two coils of which are connected respectively to the ends of R and R_x (Fig. 51). If R is graduated, one galvanometer wire is moved along it until the galvanometer gives no deflection, which will be when $R_x=R$; or if R has a fixed value, then a resistance r in circuit with one of the galvanometer coils is adjusted, until a

balance is obtained, in which case $\frac{R_x}{R}=\frac{G+r}{G}$, if G is the resistance of each coil of the galvanometer.

Although under certain conditions greater accuracy may be obtained by the fall of potential method of measuring conductor resistances, the bridge method is the one most usually employed; since the apparatus for it is more conveniently arranged in connection with that which is required for other electrical tests. The

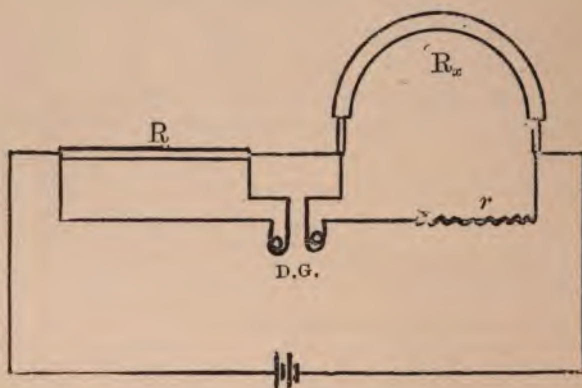

FIG. 51.

bridge may also be employed for localizing a fault in a length of cable by the loop test, the connections being made as shown in Fig. 52, where F is the fault. When a balance is obtained $\frac{BF}{AF}=\frac{R_2}{R_1}$, or $\frac{AF+BF}{AF}=\frac{R_1+R_2}{R_1}$; but (AF + BF) and AF are proportional respectively to the total length of cable, and the distance of the fault from the end A, when the resistance per unit length of the conductor is the same throughout; *and therefore* the distance of the fault from A

$= \frac{R_1}{R_1 + R_2} \times$ length of cable. When the conductor resistance is not uniform throughout, as for instance when testing leads are used to connect the terminals A and B with the ends of the cable, the conductor resistance of each section must be obtained separately by the ordinary method, so that all resistances between A and B may be expressed in terms of the resistance per unit length of the conductor of the cable under test. If the resistance of the fault is high, a considerable battery

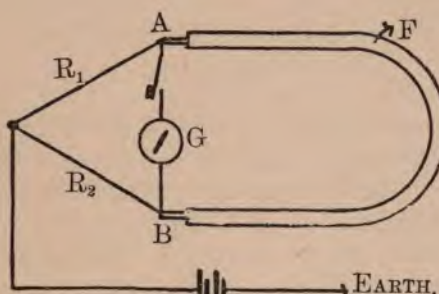

FIG. 52.

power is required to enable the test to be made with any degree of accuracy; and in the factory, where earth currents do not disturb the results, it is often more convenient to reverse the positions of the battery and galvanometer. This latter arrangement is very handy for use with the metre bridge, which may then be connected as in Fig. 53; since the distance of the fault from A may then be read off the graduated scale as a percentage of the total length of the conductor.

The insulation resistance of the cable may be measured by comparing the leakage current through the dielectric, with the current which will flow through

a known high resistance, when the same battery power is applied. The connections are shown in Fig. 54, where R is a known resistance, say one megohm; and K a key by means of which the galvanometer may be connected either to R, or to the cable to be tested.

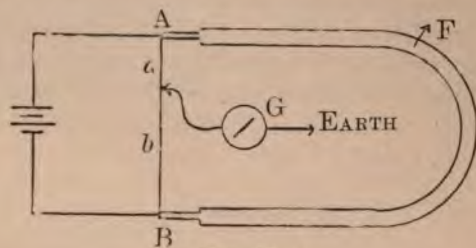

FIG. 53.

The constant is taken by closing the circuit through R, after having arranged a suitable shunt S_1, and noting the deflection θ_1 of the galvanometer. The key K is then changed over to the contact in connection with the cable, the galvanometer being short-circuited

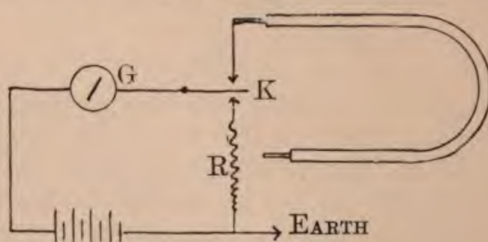

FIG. 54.

to prevent the first rush of current from passing through it. After a few seconds, the short circuit key may be opened, when the galvanometer needle will be deflected; but it will be found that the deflection is *not a* permanent one, but decreases gradually as the

current is kept on, owing to the electrification of the cable. One minute after closing the key K, the deflection θ_2 should be noted, as it is usual to specify the insulation resistance which is obtained after one minute's electrification. If a shunt S_2 has been used, the insulation resistance R_x is equal to $R \times \frac{\theta_1 \times (G + S_1) S_2}{\theta_2 \times (G + S_2) S_1}$, when G is the galvanometer resistance. The gradual decrease of the deflection due to electrification is often utilized as a further check on the soundness of the cable; as, if there is little or no electrification, or if it proceeds unsteadily, there is in all probability a fault in the cable. If the battery is taken off after electrification has been going on, say for fifteen minutes, and the cable is put to earth through the galvanometer, it will be found that a continually decreasing current will flow from the cable; and if this latter is sound, the deflections at the end of each minute will be found to correspond with those observed after equal intervals of time when the battery was on.

The measurement of insulation resistance should be made after the cable has been at least twenty-four hours in water which has been kept as nearly as possible at a uniform temperature; and the ends of the cable should be carefully prepared, so as to reduce the surface leakage to the smallest amount possible. This is most important, as, especially with short lengths of cable, it very often happens that, when this is neglected, the resistance proper of the cable is not measured at all; the deflection of the galvanometer being caused to a very great extent by the surface leakage at the ends. All tapes, braiding, or other covering, which may retain moisture, should be removed for a length of at least six inches; and the insulating material itself should be pared down with a clean sharp knife so as

to expose a new surface. The end should then be dried by allowing the flame of a spirit lamp to play round the core, care being of course taken that the insulating material is not burnt; and if the test cannot be taken immediately, the ends may be painted with hot paraffin wax. The end of the testing lead must be treated in the same way, and at the commencement of the tests, the deflection obtained when the end of the test lead is free should be noted, and should be allowed for in the subsequent readings.

It is always advisable to use as high a voltage as possible when measuring insulation resistances, so as to get a better chance of searching out any weak place in the dielectric; a convenient battery pressure being from 400 to 500 volts. This pressure may be too high to use when obtaining the constant through the standard resistance; and if this is the case, a portion only of the battery is connected, and the battery ratio is measured by comparing the discharges from a condenser, after it has been charged, first by the smaller and then by the larger battery. If the voltage of the whole battery is represented by B, and that of the part used for taking the constant by b, the ratio $\frac{B}{b}$ must appear in the formula, which will then become

$$R_x = R \times \frac{B\theta_1 (G+S_1) S_2}{b\theta_2 (G+S_2) S_1}.$$

When a joint has been made in a cable, it should always be tested, to see that its insulation is not very different from that of an equal length of the cable itself. Since the length of the joint is very small, it should offer a resistance far greater than can be measured by the direct deflection method described above; and special arrangements have therefore to be made for comparing the insulation of the joint with that of an

equal length of core. This may be done by what is called the accumulation method, or by using an electrometer. The joint in either case is immersed in water in a well-insulated trough, which may be of gutta percha or ebonite, and should be suspended by long ebonite rods. The connections for the accumulation method are shown in Fig. 55, where C is a condenser, and K a key that can connect one pole of the condenser either to the battery or to the galvanometer. The key K is closed on the lower contact, so that the

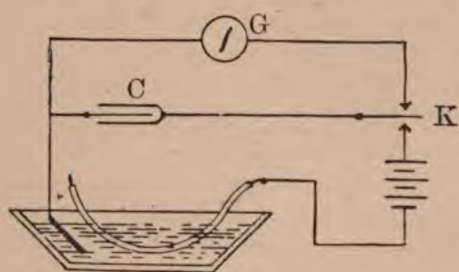

FIG. 55.

leakage through the joint charges the condenser, and is kept down for some stated time, say two minutes. At the end of these two minutes, K is switched over so as to discharge the condenser through the galvanometer, and the deflection thus obtained is compared with that given, when the joint is replaced by an equal length of perfect core. The insulation of the trough must be very good, and should always be tested beforehand. This may be done by connecting the battery so as to charge the condenser direct, and not through the joint; and then, having disconnected the battery, by allowing the condenser to stand charged for a couple of minutes before taking the discharge. If there is any appreciable leakage from the trough,

the discharge after two minutes will be less than the instantaneous discharge; and the insulation of the trough can only be considered satisfactory, when the two discharges are equal, or very nearly so.

The connections for the electrometer method are shown in Fig. 56, where E is the electrometer, and K_1, K_2, K_3, are keys for charging or discharging it. To test the insulation of the trough, close K_3 and K_1 on its upper contact, so that the small battery B_1 charges

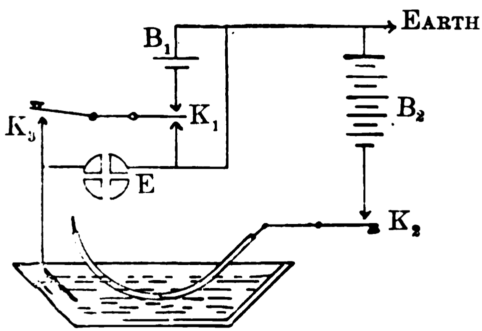

FIG. 56.

the quadrants of the electrometer, and gives a steady deflection; then open K_3, and note the decrease, if any, of the deflection, during say a couple of minutes. If this is very small, the trough may be considered to be well insulated. To test the joint, close K_2, thus charging the quadrants through the joint, and note the deflection after say two minutes, repeating the test again with an equal length of core instead of the joint; the two deflections should not differ very much if the joint is good.

The ordinary insulation test which has been described is sufficient for cables intended for low pressure work, where the strain on the cables is so

small that there is practically no chance of the current breaking through the dielectric, and where also the testing battery can be conveniently arranged to give a pressure several times as great as the working one; but for cables intended for high pressure work, a strain at least as great, and preferably greater, than that due to the working pressure should be applied, and this cannot be done conveniently with the testing battery. In such cases, therefore, a separate test should be made, in which the cable is subjected to a high pressure; and this is most conveniently done by the use of an alternating current transformer. The primary circuit of this transformer may be wound for any suitable voltage; and the secondary circuit should be divided into several separate coils, the ends of which are led to terminals, arranged so that the multiplying ratio of the two sets of windings may be varied to suit the requirements of different tests. The transformer may be wound to give a maximum pressure of 10,000 volts by steps of 1,000, or perhaps 2,000, volts per coil; and it must be capable of carrying a current of two or three amperes at least, if cables of considerable capacity are to be tested; as the condenser current may easily reach this amount, when a mile of cable is tested with 10,000 volts at a frequency say between 60 and 100 per second. For cables which are to be worked at 2,000 volts or thereabouts, a test pressure of 4,000 or 5,000 volts should be applied continuously for several hours, the cable of course being immersed in water; and after this, the insulation test should be repeated to see if there is any change in the resistance. This apparatus is also useful for breaking down a high resistance fault, and making it easier to localize by the loop test.

The capacity of the cable may be measured by com-

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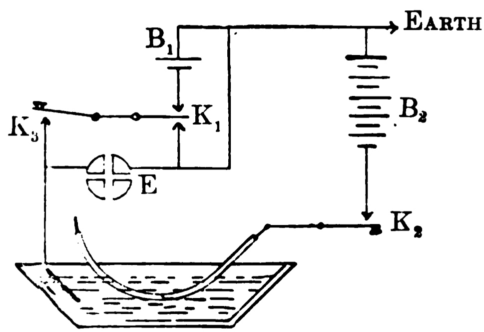

FIG. 56.

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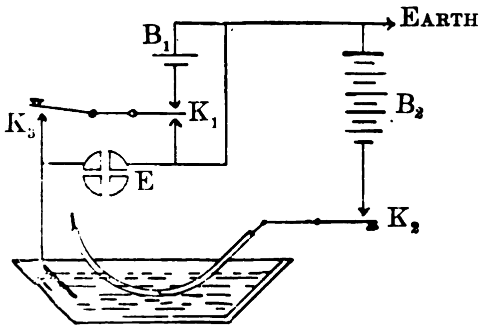

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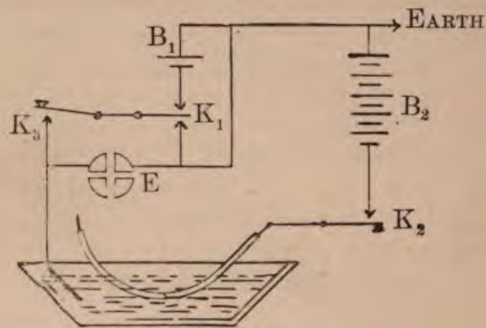

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The capacity of the cable may be measured by com-

paring the discharge from it, with that from a condenser of known capacity, the connections being made as shown in Fig. 57; where C is the condenser, and K_1 and K_2 are two discharge keys. Connect K_2 to the lower contact, and K_1 to the left-hand one, so as to charge the condenser. Switch K_1 over to the right-

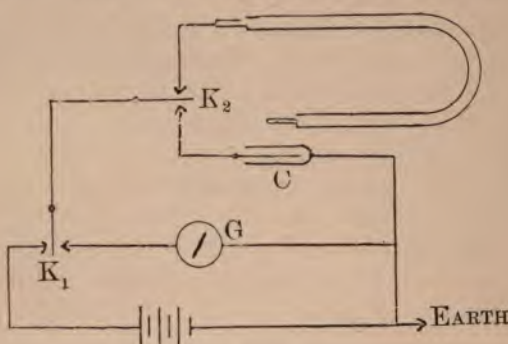

FIG. 57.

hand contact to discharge the condenser through the galvanometer, and note the discharge deflection, say θ_1 with a shunt of S_1 ohms. Having first earthed the conductor, to remove any residual charge, change K_2 over so as to connect it to the cable, and repeat the test, getting a discharge deflection, say θ_2 with a shunt S_2. Then if F_1 is the capacity of the condenser, and F_x that of the cable,

$$F_x = F_1 \times \frac{\theta_2 \times (G + S_2)S_1}{\theta_1 \times (G + S_1)S_2}$$

CHAPTER XII.

Internal Wiring.—Danger from Introduction of High Pressure in House Circuits.—Safety Devices.—Fire Risks.—Current Density.—Fusible Cut-outs.—Insulation.—Mechanical Protection.—Metal Tubes.—Wood Casing.—Paper Tubes.—Double and Single Wire Systems.—General Arrangement of Circuits.—Tree System.—Distributing System.—Testing of Circuits.

IN the preceding chapters we have seen how to determine the most economical size of conductor, and what rules must be observed to prevent the rise of temperature, due to the passage of the current, from becoming too great for safe working, and to keep the variation of pressure at all parts of the circuit within certain permissible limits; and, further, the various methods of insulating conductors have been described, and their respective advantages and disadvantages have been pointed out. It is now necessary to consider how these rules can best be applied in special cases, and how the conductors should be fixed in position, and protected from mechanical injury. For this purpose it will be convenient to discuss separately the three following cases: viz., Internal wiring, aerial lines, and underground lines.

The working pressure on circuits fitted up in buildings or ships rarely exceeds 100 or 110 volts, and is often less; so that, unless by some accident a higher pressure is introduced from external supply mains, no dangers need be apprehended from personal contact with the conductors. To guard against any accidental introduction of a dangerous pressure, the external supply mains, if directly connected to the house cir-

cuits, should not be worked at more than about 200 or 250 volts, as a leakage on one part of the circuit may expose any person touching a conductor to the full pressure; and, when transformers are used to reduce the pressure, they should be so arranged that a contact between the high and low pressure circuits is only possible when contact is also made with the earth at the same point. For this purpose the two sets of coils on some alternating and continuous current transformers are arranged in such a manner that they are divided by a metal partition which is in contact with the earth; and, when this is the case, it is evident that any leakage from one coil must go to earth before it can get to the other coil, and that the difference of potential between either of the low-pressure conductors and the earth can never be increased above that which normally exists between the two conductors.

When, as is often the case, this arrangement of the primary and secondary coils is inconvenient, a safety device, such as the one designed by Major Cardew, should be used, to automatically connect the conductor with earth if the difference of potential between them exceeds some fixed amount. The apparatus, as used by many of the Supply Companies who employ high pressure transformer systems, consists of two brass plates insulated from one another by ebonite rings and collars, and bolted together. Between them is placed a thin aluminium foil attached at one end to, and lying on the lower plate; when the difference of potential between the two plates reaches a pre-determined amount, the static attraction lifts the free end of the foil, and electrically connects the two brass plates. The plates and discs are fitted together and adjusted in the factory, and are pushed in between two sets of springs, fixed to a block of ebonite. The upper spring is connected to the

house wire, and the lower spring to earth, and the foil therefore, when it connects the two brass plates, earths the house wire, and thereby prevents a dangerous difference of potential from being maintained between any part of the secondary circuit and the earth. In practice this causes a sufficient increase of the primary current to blow the main fuse, and cut off the installation from the supply mains. The apparatus, a general view of which is given in Fig. 58, is enclosed in a

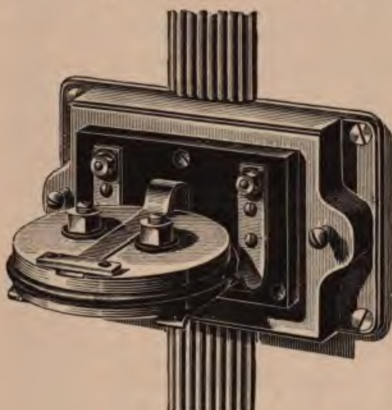

FIG. 58.

strong cast-iron box, and is fixed in any convenient position near the main switchboard.

Another earthing device on the same principle, which has been constructed by Messrs. Drake and Gorham, consists of a glass cylinder, closed at either end by an ebonite base and cap. A stout brass rod runs from top to bottom (Fig. 59), and to this is fitted an adjustable rod with a flat disc at its end; this rod being connected to the house wires. To a second terminal, which is connected to earth, is attached a brass plate, from the upper end of which is hung an aluminium foil, in such

a manner that its free end is opposite the brass disc, and can be attracted to it, when there is a sufficient difference of potential between the house wire and the earth.

It has also been proposed that some part of the

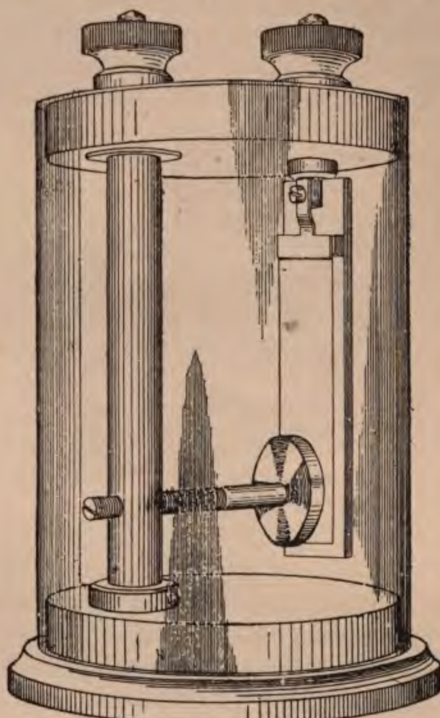

FIG. 59.

secondary circuit should be permanently earthed, such as one terminal, or the middle point of the secondary coil on the transformer; but, although this would undoubtedly render it impossible for the pressure between *any part* of the circuit and earth to become greater

than the normal working pressure in the one case, or half that amount in the other, it is objectionable because it puts a permanent strain on the insulation; and, by providing one earth ready made, insures an interruption of the light, or at any rate a serious leakage, should a fault occur in the circuit.

When any of these precautions are taken, all danger from personal contact with the conductors is removed; and the most important problem to be then considered is, what methods of arranging the conductors will best guard against any risk of fire, due to the presence of combustible material, which is always to be found in fairly close proximity to the wires in buildings or ships. The idea put forward some years ago, that, owing to the absence of flame in an electric lamp, there is no risk of fire, has been exploded; chiefly on account of the fires which have been caused by careless workmanship and the use of inferior material; and although occasionally one may come across an installation which looks as if it had been put up by some one in whose mind this idea still lingered, every electrician now recognises that dangers do exist, and, having come to that view of the matter, has set to work to render them as small as possible, by properly proportioning the area of the conductors, by more careful methods of jointing them, by the use of thoroughly reliable insulating materials, and by studying the best methods of fixing the wires and other apparatus connected in the circuit. Of course differences of opinion exist as to what is the best thing to do under given conditions, and objections may be raised to some of the methods which have been generally adopted; but it may be safely said, that perfectly satisfactory results can be obtained by following any of these different plans, if only good material and workmanship are employed throughout, and the work is

supervised during its progress by a competent foreman, who can be trusted not to pass any scamped joints, and to test from day to day to see that the wires themselves are not damaged in fixing.

The overheating of the conductors may be guarded against by making them of ample size for the normal current, and by inserting in the circuit fusible cut-outs which will melt and break the circuit, if the current by any accident becomes excessive; and the local overheating, which may be caused by a break or partial break in the conductor, or by a bad joint, can be prevented by careful workmanship and supervision, and by using wires of sufficient section and flexibility, to enable them to withstand without injury the bending and other strains, to which they may be subjected when being fixed.

Various rules for limiting the current to be carried by any conductor are specified in the regulations which have been issued by the Institution of Electrical Engineers, the Insurance Companies, and the Supply Companies. The rule given by the Institution of Electrical Engineers, viz.: "The conductivity and sectional area of any conductor should be so proportioned to the work it has to do, that if double the current proposed be sent through it, the temperature of such conductor shall not exceed 150° Fahr.," is based on very correct principles; but its application involves a knowledge of the laws regulating the rise of temperature in conductors, which is often not possessed by the contractor. If the temperature of the surrounding air be taken at 75° Fahr., the above rule is equivalent to saying that the current proposed to be sent through any conductor shall not raise its temperature more than 18° Fahr., a rise of temperature equal to that specified by the Guardian Office. For this rise, the relation be-

tween current and diameter is given in the table on p. 36; and a reference to it will show that, for the small branch wires which are mostly used in house work, a smaller current density than is allowed there is almost always rendered necessary by considerations of drop of pressure or mechanical strength.

As regards the latter, the safe limit is certainly reached with a No. 18 wire, as there is too much risk of the conductor being broken if of smaller diameter; and this wire, which will therefore be used to carry the current for only one lamp, is, according to the table, actually capable of carrying a current of six amperes, or sufficient for say sixteen lamps of 8-candle power and 100 volts pressure. If it were worked at six amperes, the fall of pressure would be at the rate of one volt for every twelve yards of conductor, or six yards run of double lead, which is a much greater fall than could be allowed for satisfactory lighting. Although the drop of pressure is not so great with larger conductors worked at their utmost safe current, it is more than can generally be allowed; since, as the number of lamps, and therefore the current, is increased, the distance of the farthest lamp from the main terminal increases also; for example, supposing the fall of pressure is arranged at an equal rate throughout the circuit, a strand of 19 No. 16 could only be worked at its maximum safe current, when the most distant lamp was about 100 feet from the terminals; and this is by no means a big allowance, when we consider that there would in this case be 250 lamps of 8-candle power on the circuit, or half that number of 16-candle power lamps.

A rule, which is often specified, allows a current density at the rate of 1,000 amperes per square inch of conductor area; and although, as regards heating of

the wire, it is wrong in principle, and actually unsafe for very large sizes, it has the great advantage of being definite and easily understood, of being fairly economical, of being safe as regards heating for all conductors up to about a quarter of a square inch area, and of keeping the fall of pressure within reasonable limits on all circuits, where the lamps are not more than 150 feet or so from the terminals. With conductors of comparatively small sectional area, like those which are most frequently used for internal wiring, a current density of 1,000 amperes per square inch allows a considerable safety margin, and a current of double the normal strength can in most cases be carried by them without undue heating. This safety margin is most useful, since the possibility of the passage of a current much greater than the normal must be considered.

Damage from overheating is usually prevented by the use of fusible cut-outs, which are arranged to melt when the current increases by some fixed percentage; and the number of these cut-outs which must be fixed, and the increase of current that can be allowed by them, depends on the safe current-carrying capacity of the wires. If the wires are in all cases only just large enough for their respective currents, a cut-out must be placed at every point where a wire of smaller sectional area is branched off a larger one; and the fuse must be arranged to melt with a very small increase of current above the normal; whereas with conductors of larger area a smaller number of cut-outs will suffice, or they can be arranged so that they will not melt without a considerable increase of current. Now, cut-outs should always be placed in easily accessible positions, and it is often difficult to arrange for this when there is a large number of them; and further, they should *never* break the circuit with the usual working current,

as many do after being in use for some time, because the natural result of such behaviour is, that the man who is looking after the lights, puts two fuse wires in instead of one, to save himself the trouble of frequent renewals, especially if he has to get a ladder or steps each time to reach up to the cut-out. A smaller number of cut-outs, fixed in easily accessible positions, with fuses so proportioned that they require about a hundred per cent. excess of current to melt them, will have a much better chance of protecting the circuits; and there is very little difficulty in arranging them on these lines so as to be perfectly safe. For example, when the smallest wire in use is a No. 18, which will carry six amperes, or say the current for sixteen 8-candle power lamps, a double pole cut-out fixed for each group of eight lamps will give ample protection; there will be but little danger of the lamps being extinguished, when the circuit is in good working order; the user of the lamps will not be inconvenienced so often by their going out; and, owing to the rarity of the occurrence, he will be far more likely to test his circuit to see if anything is wrong with it.

There is however one advantage gained by the use of a large number of cut-outs, viz., that the circuit can be divided up into a number of very small sections, which facilitates the localizing of a fault; but, if on this account cut-outs are fixed in every branch, there is still no reason why the fuses should not be all arranged to melt at the maximum current that the smallest wire will carry, so as to avoid the inconvenience of frequent renewals.

There is an old saying, that prevention is better than cure, and this holds good in the present case as in most others; so that, although the cut-out cannot be dispensed with altogether, the best way of guarding

against overheating of the conductors by the passage of an abnormal current, is to minimize the chances of leaks by the use of well-insulated wires. A well-insulated wire need not necessarily be one that gives an extremely high insulation resistance per unit length; but it must be one that gives a constant resistance under all conditions; and the material used must therefore be durable, waterproof, and capable of withstanding variations of temperature over a considerable range without permanent damage to its insulating properties, and without being rendered brittle enough to crack or soft enough to allow of the conductor sinking through it. The insulation of the conductor should be independent altogether of any help from insulating material which may be used for mechanical protection; in fact, no cable or wire should be employed that cannot stand the test of continued immersion in water; and any rule like that given by the Phœnix Fire Office (viz., that conductors should be so arranged that they will still be practically insulated in the event of their insulating coverings getting worn away or removed) is unsatisfactory; followed as it is by the recommendation of wood casing, which more often than not is a sufficiently good conductor to allow of a leakage current passing, which may char and possibly set it on fire. This plan of adding a partial insulation in series with that of the wire itself has many objections, unless the insulating casing is absolutely non-combustible; since it may render a leakage current too small to be easily detected, or to melt a fuse, and yet allow it to be large enough to cause a risk of fire; and this is exactly what is not wanted.

In the ideal installation the insulation resistance is normally high, but falls off very decidedly when a *fault occurs*, so that there is no difficulty in finding it;

and the insulated conductor is placed in such a manner that under no circumstances can a leakage current pass through any combustible material which is in proximity to it, and also so that, when a fault occurs, it may be remedied without cutting away the floor or walls of the building. These conditions may be fulfilled by fixing metal-encased wires on the surface, or by placing the wires in metal or other non-combustible tubes, into or out of which they can be drawn as occasion requires. Although these methods of construction are little used in buildings, they have been extensively employed on shipboard with very satisfactory results. Many ships are wired throughout with lead-covered cables, the dielectric being either rubber or impregnated fibrous material; these cables being fixed on the surface of the bulkheads by cleats, in such a manner that they are always exposed to view and easily accessible; and in many other ships, although wood casing is used in the cabins, the wires in the engine-room, stoke-hole, cargo spaces, etc., are run in iron pipe, provided with split T-boxes at places where branch leads are jointed to the mains. This latter method is a very good one, as the iron pipe affords an excellent mechanical protection; and, owing to its large sectional area, cannot be raised in temperature to a dangerous extent by any leakage current which is not big enough to melt the fuses. If split boxes are fixed in proper positions, the system becomes a very convenient one for drawing in and out conductors, should it be necessary to make any repairs.

For the internal wiring of buildings in England, grooved wood casings are almost universally employed; and, owing to the space occupied by them and to their unsightliness, they are very generally let into the walls, where they are out of sight, and inaccessible,

without cutting away the wall papers or other decoration. The wood casing also frequently acts as a sponge, and absorbs any moisture that may exist in the surrounding plaster; and further it does not sufficiently protect the wires mechanically, as, for instance, from being damaged by having nails driven into them. Although excellent work has been done where the wires are enclosed in wood casing, the good results are probably due more to the quality of the insulated wires and to the care in fixing them, than to any benefit derived from the use of the casing; and it is therefore somewhat surprising that such implicit reliance should be placed on it, as would appear to be the case from a study of the regulations published by Insurance and Supply Companies.

In America, a much larger proportion of the work is carried out with wires fixed on the surface of the walls, so that they are visible and accessible; and a system of hidden wiring has been introduced by the Interior Conduit Company, which provides pipes with drawing-in and joint boxes in a somewhat similar fashion to the iron pipe system already referred to. These pipes are made of paper soaked in a bituminous compound; and it is claimed for them that they are strong, tough, and waterproof, that they can be made fireproof by coating them with a suitable paint, that they are very easily fixed, and that they allow of the wires being drawn in or out as required. There is a further claim, that the bitumenized paper tube is such a good insulator, that it is unnecessary to use more than a light covering of fibrous material on the wires; but, as the two wires are run in the same tube, there would be, at any rate in our damp climate, a plentiful number of short circuits, which, although they might afford an opportunity of demonstrating the convenience

of a drawing in and out system, would hardly conduce to satisfactory working. With properly insulated wires, however, such a system has many advantages; and if the bitumenized tube is more easily fitted up than iron or stoneware tubes, it certainly deserves a trial as a substitute for wood casing.

The wiring of all buildings to which current is supplied direct from central stations, must be carried out with two insulated wires, one for the out and one for the return; but in isolated plants, and when the internal wiring is in no way connected with the supply mains, the single-wire system may be used, in which the earth or an uninsulated wire is used for the return. This system has as yet been seldom employed except for ship-lighting, in which the metal skin of the ship itself is used as the return wire; but a system, in which the return wire takes the form of a sheathing of iron wires concentric with the insulated conductor, has been developed by Mr. Andrews, and has lately been brought to the notice of the Fire Insurance Offices with a view to its introduction in land installations. Both the double wire and single wire systems, when carefully erected, will give satisfactory results; but it may be safely said that the claims made for each by their respective advocates are a good deal exaggerated.

In the single-wire system, there is a permanent earth on one side of the circuit which does not exist in the double wire, and this is claimed as an advantage by both sides; the advocates of single wiring maintaining that, since any leak must necessarily be from one conductor to the other, their circuits are completely protected by the cut-outs from all danger of over-heating and consequent risk of fire; whilst the advocates of double wiring maintain that this absolute safety does not exist, and that the permanent earth on the system

puts a continual strain on the insulation of the dynamo machine and the out-going wire. If we consider these claims rather more in detail, we shall see that both may be right or both wrong, according to the way in which the work is carried out. For instance, we have seen that it is not advisable to arrange for the fuses to melt with a very small increase of current above the normal, because of the inconvenience caused by their melting with the normal current after being in use for some time; and a leak therefore may exist for a considerable period before the fuse goes, and may be a cause of fire if, on its way to earth, the leakage current passes through a semi-conducting combustible material like wood casing. If, however, the out-going insulated conductor is entirely surrounded by a non-combustible material, which is also a good conductor and is efficiently connected to earth, as would be the case with the Andrews armoured cable, or when the insulated conductor is run in an iron pipe, then, although a leakage might occur which would not be sufficient to melt the fuse, and would therefore remain undiscovered, it would still have no chance of causing a fire, since there would be nothing combustible in its path. There would still, however, be the disadvantage of the greater strain on the insulation of the out-going conductor and dynamo, which may be taken roughly at twice the strain in a double-wire system; but this may be provided for by spending rather more on insulating material, and need not therefore be counted, when comparing the two systems when each is at its best.

The fact that there is no chance, with single wiring, of discovering and remedying a fault, before it has caused a breakdown, is of considerable moment. A double-wire system may easily be arranged in such a manner that, in ninety-nine cases out of a hundred, the

fault will take the form of a leak to earth; and as the circuit can be worked all right with one earth on it, and the existence of this earth can be discovered even whilst the dynamo is running, there is always an opportunity of remedying the defect before it causes a breakdown. With the single wire system, on the other hand, it is impossible to measure the insulation resistance of the circuit without removing all the lamps; and the development of a fault, of which there is no warning, will cause a short circuit, which will, if in the circuit, extinguish some of the lamps, and if in the dynamo machine whose winding cannot be protected by cut-outs, burn out the coils.

A claim is also made on behalf of the single wire system, that only half the amount of wire is required, and that it is therefore much cheaper. That it may be cheaper there is no doubt; but, if equal insulation is provided, and the concentric form of conductor is used, the difference will be very much less than is often supposed; and even if ordinary wires are used in wood-casing, the cost of running return wires from the lamps to the hull of the ship, and connecting them thereto, must be taken into account. These connections have sometimes been a source of trouble, through corrosion at the point of contact between the wire and the framework of the ship, with the result that an extra resistance is introduced; and as the connections are not generally in accessible positions, it is difficult to get at them and overhaul them.

With regard to the effect of the current on the ship's compasses, it is now generally acknowledged that all wiring, within say 20 or 30 feet of a compass, should be carried out with an insulated return, so as to avoid the errors produced by the unbalanced effect of a current in one direction; but Sir William Thomson,

in a paper read before the Institution of Electrical Engineers in 1889, pointed out that even with this precaution an error would still exist, owing to the hull of the ship being connected as a shunt on the insulated return wire, so that the currents in the out-going and the return conductors would be unequal. The same error may exist in a ship with double wiring, if two points on the same side of the circuit make connection with earth, one leak being between the dynamo and the compass, and the other beyond the compass; but in this case the fault can be remedied by repairing the insulation of the wire, whereas with single wiring the use of the hull as a return is an integral part of the system. The comparative merits of the two systems may then be summed up briefly thus:—The single wire system may be fitted up at a smaller cost than the double wire, though, when fitted in the most efficient manner, the difference of cost is not great; whilst the double wire system is generally speaking more trustworthy, and has the very great advantage that the state of the circuits can be ascertained at any time by testing, and that a fault, should one exist, can be remedied before it causes a breakdown.

With either of these systems, the general arrangement of the conductors may be carried out in two different ways. In one (fig. 60), which may be called the tree system, branches are taken off the main conductors, and from these branches others are taken, the branching off being continued until finally the lamp wire is reached; and in the other (fig 61), which may be called the distributing system, a large number of small circuits start from one or more distributing boards, each of which may be connected by its own pair of cables to the main switchboard.

The second, or distributing, system has recently come

into great favour, and is now very extensively employed; since, although it is not so economical in wire, it reduces the number of insulated joints in the circuit to those required for the actual lamp branches; and these joints are always the weakest part of the insulated wire, and have frequently to be placed so that they are difficult of access. In some cases the wiring is arranged

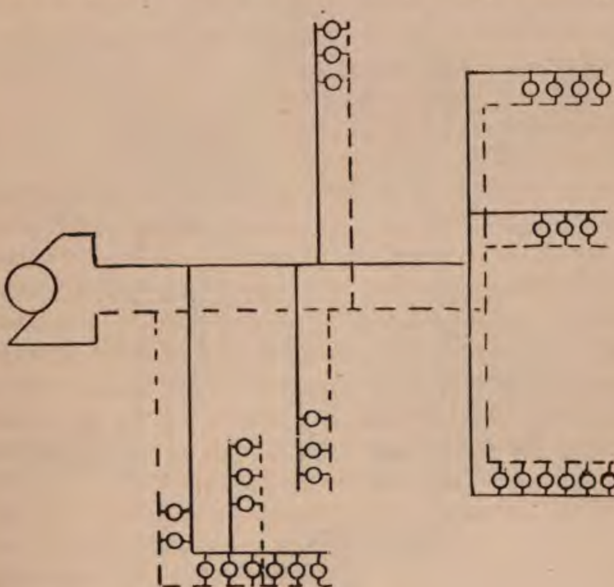

FIG. 60.

so that there are no insulated joints in the circuits at all; for example, in an ordinary house a distributing board may be fixed near the dynamo or other source of current, and from this a separate circuit may be run to a distributing board on each floor; from these, circuits may be run to a board in each room, from which separate wires are run to each lamp; or a separate

circuit may be run to each room from the main distributing board, thus doing away with the board on each floor. This method of wiring, besides doing away with all joints, allows all the cut-outs to be grouped together on the distributing boards, where they are easily accessible; and, if more convenient, the switches

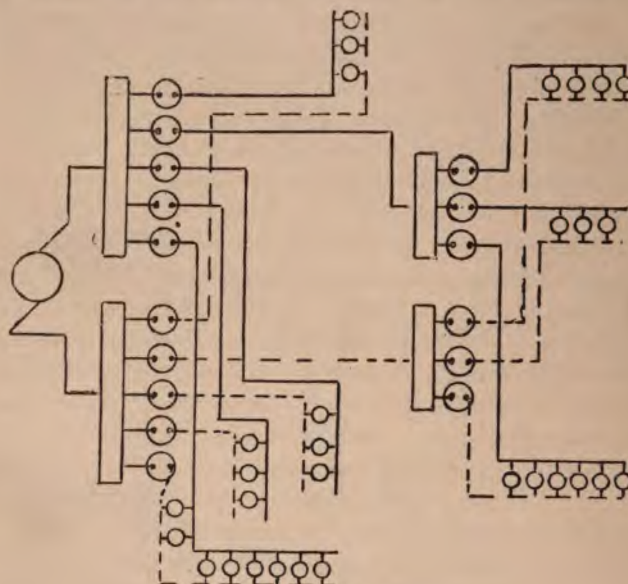

FIG. 61.

also may be fixed on these boards, or may be grouped together near the doors of the various rooms.

This arrangement of circuits, combined with a system of pipes into or out of which the wires may be drawn and with cut-outs fixed on distributing boards, so that they each control a circuit of 8 or 10 lamps, will give the most satisfactory results; since the insulation of the wires is left intact throughout their whole length,

which decreases the chance of leakage from them; repairs, if necessary, can be made without interfering with the decorations of the walls; and the cut-outs are visible and accessible, and may be more easily arranged so that they themselves cannot, by failing to work properly, be the cause of a fire. Of course the smallest wire on any circuit must be large enough to carry the fusing current of the cut-out without injury; and this, together with the use of a much greater length of comparatively small wire instead of a short length of larger wire, will increase the cost of the wires and casings; but the saving of labour in jointing, and the smaller cost of the cut-outs, will to a great extent, if not entirely, counterbalance any increase of cost on this account.

Whatever arrangement of circuits and methods of fixing the wires are adopted, the final result must depend on the quality of the material and workmanship; and, to ensure that this is good, there must be constant supervision by a competent foreman, and frequent tests of the circuits whilst the work is in progress; so that faults, either in the conductivity or insulation of the wires, may be at once located and removed. Several very useful and compact portable testing sets are on the market, with which the conductivity and insulation resistances of the wires may be measured; and if these tests are systematically taken day by day, no faults need be allowed to pass unnoticed. Too frequently the testing of the circuits stops when the Insurance Office or Supply Company have passed the installation, and most users of the light consider that this must be so, since they themselves are not electricians; but there are several very simple methods of detecting the existence of a leakage whilst the current is on; and it would be to the interest of all parties, if suitable apparatus were fitted up as part of the installation, and the user

of the circuit would test it every day. Several of these methods are described in Chapter XVI., the lamp method being the simplest and least expensive, when switches are provided so that the lamps are out of circuit except at the times when a test is being made.

CHAPTER XIII.

Overhead Lines.—Objections to their Use.—Materials for Overhead Lines.—Wire and Cables.—Bearer Wires.—Poles.—Insulators.—Lightning Protectors.—Bare Wire Line.—Cable Line.—Cable Line with Bearer Wires.—Earthing the Bearer Wire.—Mechanical Strains on Wire and Poles.—Calculation of Strains.—Average Wind Pressure.

For outdoor work the conductor may either be placed overhead or underground, each method having certain advantages over the other; and a decision as to which is the better to use for any particular installation can only be arrived at after all the conditions of the case are known. There are, however, certain points which must be taken into account in any comparison between the two methods of placing the conductors, such as their relative costs both as regards capital expenditure and maintenance, and their relative safety to the public.

In the matter of first cost, the advantage is decidedly on the side of the overhead wire, except when very large conductors are employed; as the trenching, and pipes or other conduits, required for the underground main are much more costly than the poles and insulators which support the overhead wire; but, as a general rule, it may be taken that a well insulated cable safely laid underground will cost less for maintenance than if placed overhead, owing to the fact that it is not exposed to the same extent to the chance of mechanical injury from storms of snow and wind, or from lightning strokes; and that it is placed in such a position that variations in atmospheric conditions can

have little effect on it. Much will depend on the class of cable used, and on the degree of efficiency, as regards insulation, which is considered necessary; as, with an inferior class of cable, the underground main may be very expensive to maintain on account of continual failures of the dielectric, which must be repaired to enable working to be continued; whilst with the overhead wire the insulation of the cable is supplemented by that given by the supports, and this latter may have sufficient resistance to allow of the line being worked.

It is, however, when the safety of the public is considered that the expense of maintaining the overhead line is increased; as, if high pressures are used (and it is only in such cases that there is much to be gained in first cost), the cables must be quite as well insulated as those required underground; and the line must be periodically inspected, and poles, stays, bearer wires, etc., replaced, as they show signs of deterioration, so as to avoid all chance of injury through the breaking of any one of them. At intervals of a few years, judging from the experience of the Post Office and of the Telephone Companies, a wholesale renewal of much of the system of overhead lines takes place, owing to their destruction by a violent gale of wind accompanying a snow storm; and the possibility of such an occurrence must be taken into account, and the overhead line must either be made so strong mechanically that it can withstand such storms—and this means a considerable expenditure of capital—or one must be prepared for an occasional breakdown with the consequent loss of business and cost of renewal.

For these reasons it will be found more economical to place the wires underground, except in districts where the houses requiring the current are very scattered, or

a new district is being exploited; in which case, or when electricity is transmitted to a considerable distance for driving motors, etc., it may often happen that an underground line is not possible commercially; for example, if water power can be obtained at a distance of several miles from a mill or factory, and it is proposed to erect turbines and dynamos at the one place and motors at the other, it may happen that the interest on an underground line, added to that of the other plant, will come to as large a sum as the annual cost of power derived from another source; and therefore, that, unless an overhead wire can be used, the scheme will be dropped altogether.

The objections to the use of overhead lines, briefly stated, are their liability to mechanical injury through wind storms, to electrical injury from lightning, and the possibility of accidents being caused by the breaking of the conductor, or by its contact with a human being or with other conductors. None of these objections present any very serious difficulty, and they may all be overcome by the use of good material, careful erection, and efficient inspection at frequent intervals after the line is working; but this all adds to the expense, and, unfortunately, much of the overhead work that has been done has been put up for cheapness, and therefore in the worst manner possible; with the result that accidents have happened, and a great outcry has been raised against all overhead wires, and their use has been condemned indiscriminately. In large towns it is advisable not to use aerial lines, because it is often difficult to keep down the length of the span at street crossings, so that there is a greater chance of accidents happening from a broken wire; and, when such accidents occur, they may be more serious in the towns than elsewhere; but these objections do not apply with

the same force in many smaller towns, or in the open country, and there is, therefore, no reason for preventing the erection of overhead wires in such cases, when economy results from their use. Two cases may be considered: one in which the line is carried on poles across country, and consists of bare wires; and the other in which the line is carried over the housetops, or along the side of the public roads, in which case the wire must be continuously insulated.

The bare wire line must be erected in such a way that the conductors cannot come into contact with one another, or with any neighbouring wire, tree, or other substance that might cause a short circuit between them; and also so that it is difficult of access to the public, who should have no chance of accidentally making contact with the conductors. The cable line, though free from the chances of contacts, is more liable to be broken mechanically; since the weight of the insulating material, and the larger surface exposed to the wind add considerably to the strains on the conductor, unless the latter is relieved by a special steel bearer wire being run from which the cable is suspended at short intervals.

The materials required for an overhead line, in addition to the conductors, are poles of wood or iron, insulators, bearer wires, struts and stay wires, and lightning guards. When bare, the conductor is generally of hard drawn copper, or silicon bronze; these materials giving, as we have seen in a preceding chapter, better results than steel or iron, when conductivity, breaking strain, and weight are all taken into account. Hard drawn copper can be obtained with 97 per cent. of the conductivity of pure copper, its breaking weight is 64,000 a, or 50,000 d^2 pounds, where a is the area and d is the diameter of the wire in

inches; and its weight is equal to 3·86 a, or 3·03 d^2 pounds per foot run. When insulated the conductor is most generally a soft copper wire or strand, in which case, except for very short spans, the strain should be taken off the copper, and should be borne by a separate bearer wire, which is generally a strand of galvanized steel wires weighing say 3·4 a pounds per foot run, and having a breaking strain of 90,000 a pounds, where a is the area of the strand in square inches.

The best wood for poles is the Norway red fir, although larch and Scotch fir are also employed. It is usual to specify the dimensions required, and that the poles shall be winter felled, and contain the natural butt of the tree, sound and hard grown, straight, free from large knots and other defects, and that they shall have the bark completely removed. Poles from 20 to 30 feet long should not be less than 5 inches diameter at the top, and from 7 to 9 inches at the ground line, that is say, 5 feet from the butt end; and they should always be creosoted to preserve them. According to the results of experiments carried out by the Post Office authorities, in 1885, at their Gloucester Road factory, the strength of such poles is given by the formula $P = 63{\cdot}7\frac{D^3}{L}$, where D is the diameter of the pole in inches at the ground line, and L the distance in feet from the ground to the point at which the resultant strain P is applied; and this value divided by the factor of safety of 4 or 6 will give the safe working pressure. When iron poles are used they are generally made with a cast iron lower tube, into which is fitted a tapered tube of wrought iron; or, when the poles are much more than 20 feet long over all, two wrought iron tubes socketed into one another are fitted to the cast iron tube. In some cases a buckled plate

of wrought iron (see fig. 62) is attached to the base of the cast iron tube, so as to add to the stability of the pole when set in the ground; or the tube may be

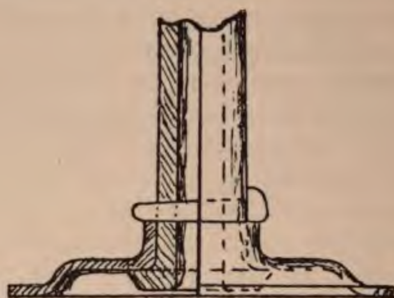

FIG. 62.

fitted with two cross-bars set at right angles to one another (see fig. 63); whilst in others the cast iron tube is made with a pointed shoe at its lower extremity, so

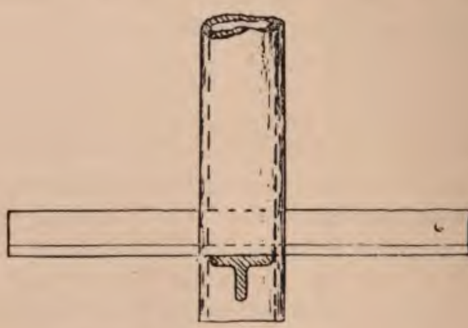

FIG. 63.

as to form a pile, which may be driven into the ground without first digging a hole to receive it (see fig. 64). When the line is straight, and the locality one which

is free from strong gales of wind, the stability of the pole as set in the ground is generally sufficient; but when it is subjected to considerable side strains from wind pressure, or from change of direction of the line wire, it is necessary to stiffen it by providing struts or stays, so placed that their point of attachment to the pole is as near as possible to the point at which the

FIG. 64.

resultant pressure is applied, and that the line along which this pressure acts is in the plane passing through the pole and stay, or strut. Good anchorage must be provided for a stay to prevent it from pulling out, and this is often obtained by attaching the lower end to a baulk of timber buried in the ground; it is also advisable to bury a flat stone or piece of timber under the foot of a strut, to give a larger bearing surface, and prevent it from being driven into the ground. For housetop lines iron poles are generally used, and are fitted into saddles placed on the ridge of the roof, so that the downward pressure may be distributed over

a large surface (see fig. 65). Poles fixed in this manner have no stability in themselves, but must be stayed in three or more directions, the downward pressure of the stay, and their own weight and that of the line, all combining to hold them firmly in place in the saddle. The strength of iron poles may be varied within very wide limits, according to the relative values given to their length and diameter, and to the thickness of metal: and it may be taken that the

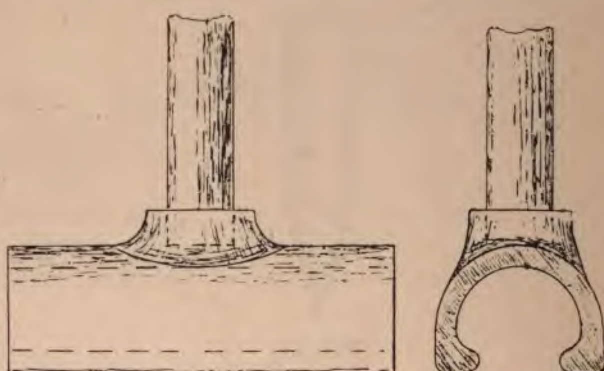

FIG. 65.

following expression will give a safe working pressure applied near the top of the pole, viz.: $P = 80\frac{D^4 - d^4}{DL}$

where P is the resultant pressure in pounds,

D and d are the outer and inner diameters in inches of the wrought iron tube at its base, and

L is the distance in feet from the ground line to the point at which the resultant pressure is applied.

The wires, whether bare or insulated, are generally supported on porcelain insulators of one or other of three types, viz.: the ordinary double-bell insulator, the

shackle insulator, or the oil insulator. The porcelain should be dense and of fine grain, uniform throughout, and free from cracks or flaws, and should be glazed all over. The double-bell insulator, as ordinarily made, is shown in fig. 66, and has grooves at the top and at the

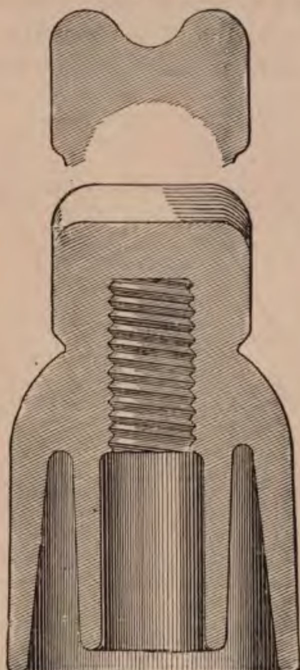

FIG. 66.

side, in one of which the wire is laid, and is fixed by lashings which lie in the other groove. The oil insulator is similar in many respects to it, but the bell is formed into a cup, as shown in fig. 67, and this cup is filled with oil, to diminish the amount of surface leakage. The insulator is fitted with a bolt which is

cemented in place, and is attached to a bracket fixed to the pole in the manner shown in fig. 68, which represents a method of attachment frequently used with wooden poles.

The shackle insulator (fig. 69) is used when the strain in the wire is considerable; as, although much inferior to either of the forms already mentioned as regards its insulating qualities, it is better adapted from

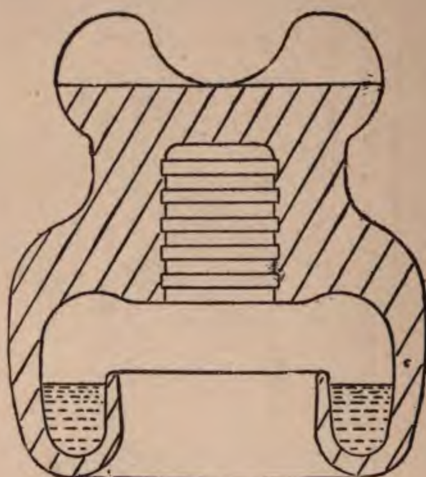

FIG. 67.

a mechanical point of view for withstanding the pull from the wire.

It is carried by two straps attached to it by a bolt passing through it from end to end, and the straps themselves are carried by a bracket or clip fixed to the pole.

Overhead lines are exposed to the chance of being struck by lightning, and precautions must therefore be taken to prevent injury to the line or apparatus connected to it, from this cause. To protect the line, a

lightning rod is carried up some distance above the top of the pole, and is efficiently connected to the earth at its lower extremity; and, in addition to this, when

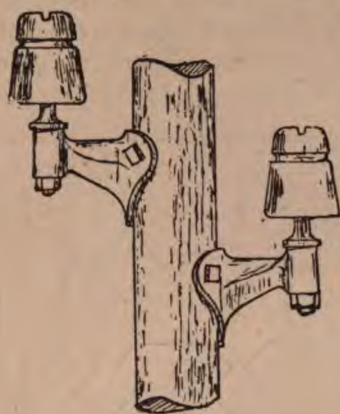

FIG. 68.

bare wires are used, a branch rod is arranged for each insulator, so that its point is within a very short distance of the wire. To protect the dynamos and

FIG. 69.

other apparatus, lightning protectors are fixed in the line on both the outgoing and return conductors, and are arranged in such a way that a small air gap sepa-

rates the line wire from an earth connection; this gap being somewhat greater than the sparking distance in air for the pressure employed on the line, but small enough to allow of the lightning discharge leaping across it. In England, where we are not so subject to violent storms as in many other countries, comparatively little attention has been paid to the design of protectors,

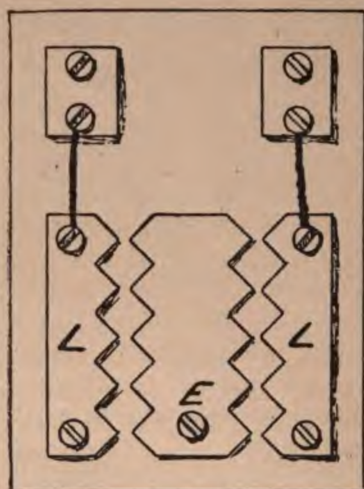

FIG. 70.

which will, after allowing the discharge to pass, automatically break any connection to earth caused by the maintenance of an arc by the working pressure. Fig. 70 shows a simple form of protector which may be used when no automatic circuit-breaking apparatus is necessary, the two plates being shaped so that there are several projecting teeth on each of them which approach one another very closely.

In America, where high-pressure overhead lines are numerous, and severe storms more frequent, several

very ingenious forms of lightning protectors are in use, which break the earth connection as soon as a discharge has taken place, and still leave the apparatus in working order and ready for another discharge, should one come. The best examples of American practice are the lightning protectors used in conjunction with the Thomson-Houston and Westinghouse systems; the former type depending for breaking the arc on the repelling effect on it of an electro-magnet, whilst the latter depends on the action of an air blast produced by the expansion of the air in a closed chamber, which results from the heat of the arc itself. The protector used by the Thomson-Houston Company on their arc light circuits consists of an electro-magnet in series with the arc lamps, and two insulated metallic plates, which are curved in such a manner that they approach very close to one another at their lower extremities, but that the distance between them gradually increases, (as shown in fig. 71,) towards their upper extremities. One of these apparatus is placed in the positive, and one in the negative line wire, between the overhead line and the dynamo terminals; the wire from the dynamo being connected to the bottom left-hand terminal, so that the current passes round the magnet coils and thence to the plate L, to which the line wire is attached. The other plate, E, is connected to the earth. If the line is struck, the discharge leaps across the small gap between L and E, and so gets to earth, in preference to passing through the coils of the electro-magnet; but the arc thus formed, if maintained by the high pressure employed on the circuit, is then in the magnetic field between the two pole-pieces, and is repelled upwards toward the part where the air gap is much greater, and is thus extinguished. The protector used by the same Company on high pressure trans-

former circuits is somewhat similar in principle; but the electro-magnets are not in the main circuit, but in the discharge circuit. To protect a transformer, the line wires are brought to two terminals, from which they pass on to the transformer. To each of these terminals is connected one end of the coil of an electro-magnet,

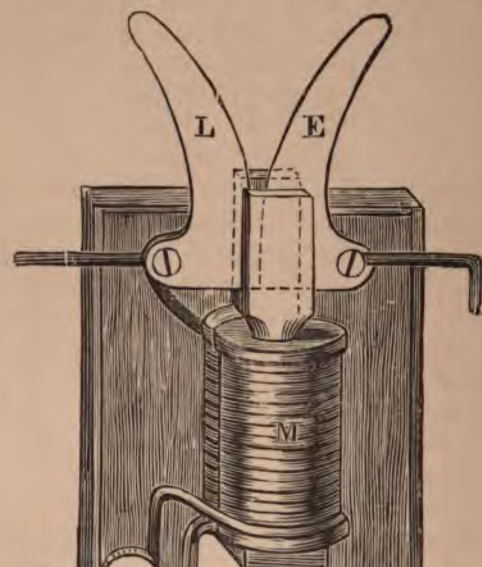

FIG. 71.

the other end being attached to a terminal in close proximity to a plate which is connected to earth. If the line is struck, the discharge passes through the coil and jumps the gap between the terminal and the earth-plate, this gap being so placed that the magnetic field, due to the current round the magnet coil blows out the arc.

The Westinghouse arc light circuit protector* is shown in fig. 72; B is a carbon ball connected to

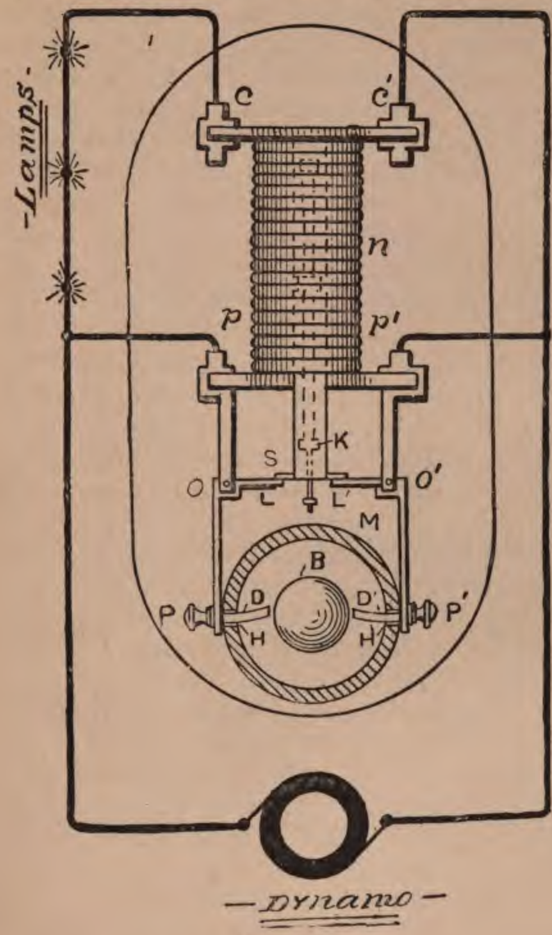

FIG. 72.

earth, and enclosed in a box M, through the walls of which enter two electrodes, D, D′, each of which is

carried on a bell crank pivoted at O, O′, and is separately adjustable by means of thumbscrews P, P′, by which the distance between the point of each electrode and the carbon ball can be regulated at will. A solenoid *n*, whose coil is in series with the arc lamps, is so placed that, when no current flows round it, its core, K, drops on the short arms, L, L′, of the bell cranks, and, by depressing them, draws the electrodes further away from the carbon ball. If the line is struck, the discharge passes through the terminals *p*, *p′* to the electrodes, and jumps the gaps separating them from the carbon ball. If the arc is maintained by the dynamo current, the solenoid is short-circuited; its core drops, and, striking the arms L, L′, separates the electrodes and the carbon ball by a greater air space. The heat generated by the arcs thus formed causes the air in the closed chamber to expand, and forms a blast, which escapes through the holes H, H′, and blows out the arc. As soon as the arc is broken, the current passes once more round the solenoid, and causes the core to rise, allowing the electrodes to take up their normal position again.

The protector used by the Westinghouse Company on their transformer circuits consists of two closed boxes *a*, *a′* (fig. 73), each of which has an opening, *c*, *c′*, leading into the tubes *d*, *d′*, and contains two carbon points, *h*, *i* and *h′*, *i′*, separated from one another by a gap of about one-eighth of an inch. Just above the opening leading into each tube is placed another pair of carbons, *f*, *e* and *f′*, *e′*, separated by similar air gaps, which are however short-circuited by carbon balls, *j* and *j′*. The carbons *i*, *h′* are connected to the earth; *h* is connected through the carbons *f*, *e* and the ball *j* to one line wire; and *i′* is connected through the carbons *f′*, *e′* and the ball *j′* to the other line wire. If the line is struck, the discharge passes by way of the upper sets

of carbon points and balls to the lower carbons, and jumps the air gaps, thus passing to earth. The heat, due to the arcs formed at *o*, *o′*, expands the air in the

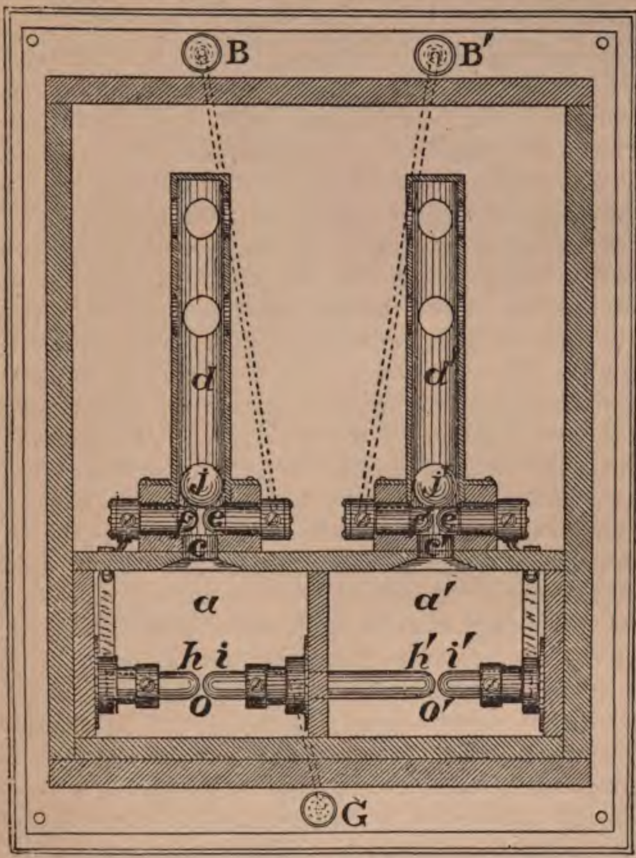

Fig. 73.

closed chambers, and the blast due to this expansion forces the carbon balls upwards in the tubes, and breaks the connection with the line wires. As soon

as the arc is broken, the carbon balls fall back into their normal positions, and once more complete the connection between the line wires and the carbons h, i', so that the apparatus is ready to act again should another discharge occur.

When designing an overhead line, it is necessary to consider the mechanical strains to which the line and its supports will be subjected, as well as the current-carrying capacity of the conductor and its insulation. The size of the conductor for an overhead line must be determined in the manner already explained; that is, in accordance with the law of economical current density, except when the conditions of working are such that the size of the conductor must be settled by its current-carrying capacity, or by the fall of pressure along it. The insulation may be effected by supporting a bare wire on porcelain insulators, or by using a continuously insulated conductor, which may be suspended direct from the insulators, or from special bearer wires. As we have already seen, the bare wire is only admissible when the line can be so placed that there is practically no chance of any person, or of any other wire making an accidental contact; and therefore such lines are rarely used in England, although many examples of them may be found in other countries. They are especially useful when power has to be transmitted some distance across country, as the cost of insulated cables would often be so great as to prevent the erection of the line. Wood or iron poles may be used with the ordinary double-bell or the oil insulator carried on brackets fixed to the pole. The two lines should be carried one on each side of the pole, as shown in fig. 74, and one at a higher level than the other, so as to prevent the two wires from swaying into contact when set in motion by the wind.

Continuously insulated conductors are often erected in exactly the same manner; and where the spans need

Fig. 74.

not be very long, and the line is not in an exposed position, this method answers very well. The bell-shaped insulators are however sometimes replaced by

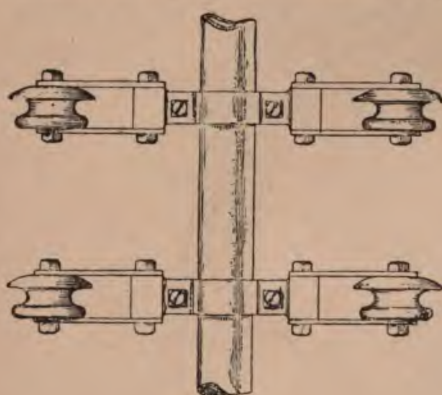

Fig. 75.

shackle insulators, which are then arranged as shown in Fig. 75. This plan would be objectionable when

bare wire is used, as the leakage is much greater with these insulators than with those of the double-bell type.

For housetop lines, where the spans are often of considerable length, owing to the difficulty of obtaining wayleaves, and the necessity of crossing wide streets, and where the line is more exposed to the wind, the

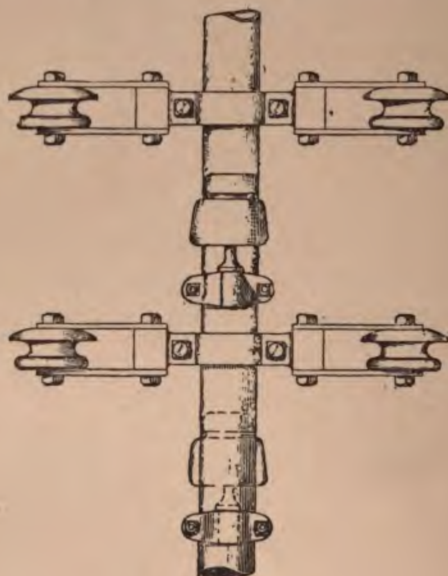

Fig. 76.

insulated conductor is generally supported by ties from a bearer wire; these ties being placed at intervals of about 3 feet. When the bearer wire is attached to insulators, as is generally the case, shackle insulators are used, arranged as shown in fig. 76; the cable being attached to an insulator fixed at the side of the pole. The bearer wire, although increasing the cost, is neces-

sary for all housetop lines; as it relieves the cable from all tensile strain, and greatly diminishes the chance of a break in the conductor, an accident which might have serious results in large towns.

Another advantage of the use of a bearer wire is, that it does away with the strain on the cable at the points of support, and consequently diminishes the chance of damage to the insulation at that place; a chance that must always exist even with the most careful erection. We said that the bearer wire was generally attached to insulators, and this must be done wherever the line is put up under the Regulations of the Board of Trade; but it is by no means certain that this way of erecting the line is the best. The avowed object of insulating the bearer wire is to add additional insulation in series with that of the cable; and it certainly may allow of a line being worked when the cable itself is faulty; but this, instead of being a real advantage, may often be the exact opposite. The outer covering of tapes or braiding becomes a very fair conductor in wet weather, as also do the suspensions by which the cable is hung from the bearer; and consequently, if there is a fault in the insulation of the cable, the braiding, suspensions, and bearer wire may all be put in electrical connection with the conductor, with the result that a contact with any of them is equivalent to a contact with the conductor itself. Even if the insulating covering of the cable is perfect, an unpleasant shock may be got by contact with its outer surface, and in damp weather, therefore, from the bearer wire also; indeed, the bearer wire, being a good conductor and connected at frequent intervals to the cable by semi-conducting material, becomes equivalent to a metallic sheathing; and it is universally recognised that any metallic sheathing on a

cable working with high pressures must be earthed. The conditions under which a shock may be received from contact with the outside covering of the cable have been referred to in Chapter VII., where some figures were given showing that the current passing might be dangerously great. It would therefore be much better to use a cable insulated in such a manner as would render the supplementary insulation of the bearer wire unnecessary, and to connect this latter to earth. Besides the advantages already mentioned, the earthing of the bearer wire would render it a sort of lightning protector for the line, as there would always be just above the cable an easy path to earth; and further, it would make the attachment of the wire to the pole a stronger and easier job mechanically, and it would somewhat reduce the cost of erecting the line.

We must now consider the mechanical strains to which an overhead line may be subjected, and the laws which govern them. When a wire is suspended between two poles, the tensile strain tending to break the wire is due, partly to its own weight, and partly to thepressure of the wind on its surface; it is greater as the span or distance between the poles is increased, and less as the sag or dip of the wire is increased. The law which determines the strain at the point of support, and this is where the greatest strain occurs, is as follows, $\frac{t}{w}=\frac{a^2}{8d}+\frac{7d}{6}$; which, when the dip is not excessive, may be simplified to $t=\frac{a^2w}{8d}$, where

t = strain at insulator in pounds
a = span in feet
d = dip in feet
w = resultant pressure in pounds per foot run.

The resultant pressure has for its two components

the weight of the wire per foot $= W$, and the pressure of the wind per foot $= P$; and as these two forces act at right angles to one another, since the direction of the wind is supposed to be along a horizontal line, we may write $w = \sqrt{W^2 + P^2}$. The direction of the wind is taken at right angles to the axis of the wire, as this direction gives the maximum strain of any, the value of P being calculated from $P = \cdot 05pd$, where p is the pressure in pounds per square foot on a plane surface at right angles to the direction of the wind, and d is the diameter of the wire in inches. The constant ·05 contains a coefficient, which represents the ratio of the effective pressure on a cylindrical surface to that on a plane surface; and for this coefficient the value 0·6 has been taken as a fair mean of the values which have been assigned to it by different writers, the éxact value being somewhat doubtful from the want of accurate experimental data.

The formula given above may be written $d = \frac{a^2 w}{8t}$, or $a = \sqrt{\frac{8dt}{w}}$; and it is in one or other of these forms that it is of most use, as the values of t and w are fixed when the size and material of the conductor is decided; and, with these data given, we have to find, for a given span, what dip must be allowed, or, for a given maximum dip, what is the longest span that can be safely used.

The strains on the poles are a crushing strain due to the weight of the wire, and to the vertical component of the tension in the stays, if there are any; and a bending strain due to the pressure of the wind on the wires and pole, to a change in the direction of the line, or to the pull of the wires in two adjacent spans

being unequal. The crushing strain due to the weight of the wires is equal to the sum of the products aW for each wire; and that due to any stay wire is equal to the product of the tension in the stay into the cosine of the angle it makes with the pole. The side strain due to wind pressure is equal to the sum of the products aP for each wire, plus the pressure on the surface of the pole, which equals ·05pD multiplied by the length of the pole in feet. The side strain due to a change in the direction of the line is most easily obtained by drawing a parallelogram of forces; but, in the usual case, where the tensions t and t' in the two neighbouring wires are equal, the strain $= 2t \cos \frac{a}{2}$, where a is the angle enclosed by the two wires at the support. The strain at a terminal post, or at a pole where the tensions in the two wires are unequal, is obtained by calculating the value of t for each wire and taking the difference between them.

In any of these cases, if the resultant pressure tending to bend the pole is greater than $15\frac{D^3}{L}$ for wood poles, or $80\frac{D^4 - d^4}{DL}$ for tubular iron poles, stays must be fixed to stiffen them; and these stays should be attached as near as possible to the point at which the resultant pressure acts, and in the same vertical plane with it. The strain in the stay wire will be equal to the resultant pressure, divided by the sine of the angle between the pole and the stay wire, if the latter is attached to the pole at the point at which the resultant pressure acts; and if not, but at a height L′ above the ground, then the value given above must be multiplied by $\frac{L}{L'}$.

Let us consider an example of a bare wire line, of a

cable line without bearers, and of a cable line with bearers; first on the assumption that a wind pressure of 20 pounds per square foot is to be allowed for, and that the usual factor of safety of 4 is to be used; and then that the wind pressure is 50 pounds per square foot, and that a factor of safety of 6 is to be used, these latter figures being those that are specified in the regulations drawn up by the Board of Trade.

Bare wire line of two conductors, each of 7 strands of No. 16 L.S.G. hard-drawn copper. The area of this conductor is ·0228 square inches and the diameter ·192 inches. The weight per foot run $W = 3{\cdot}86 \times {\cdot}0228 = {\cdot}088$, and the safe working tension with a factor of safety of four is $t = \frac{64000 \times {\cdot}0228}{4} = 365$. The wind pressure per foot run $P = {\cdot}05 \times 20 \times {\cdot}192 = {\cdot}192$, when $p = 20$ lbs. per square foot. $w = \sqrt{W^2 + P^2} = \sqrt{({\cdot}088)^2 + ({\cdot}192)^2} = {\cdot}211$. If we take a span of 200 feet, the dip will be $d = \frac{200 \times 200 \times {\cdot}211}{8 \times 365} = 2{\cdot}89$, or say 2 feet $10\frac{3}{4}$ inches. It must be remembered that this is the minimum dip that can be allowed with safety; and therefore the wire should be strained so that, at the lowest temperature it is likely to reach, there will be this amount of dip. At higher temperatures the dip will be greater, owing to the expansion of the wire; and this should be taken into account, if the line is fixed when the temperature of the atmosphere is not at its lowest. This may be done by calculating the length of the wire in the span by the formula $s = a + \frac{8d^2}{3a}$, and adding to it the number obtained by multiplying it by the coefficient of expansion per degree, and by the number of degrees that the temperature is above the minimum. With this new value s' we can then calculate the dip d' from

the same equation, which may also be written $d' = \sqrt{\frac{3a(s'-a)}{8}}$. For example, suppose that a fall of temperature of 40° Fahr. is to be allowed for; the coefficient of expansion for copper being $\frac{9\cdot56}{10^6}$, we should proceed as follows:—

$$s = 200 + \frac{8 \times (2\cdot89)^2}{3 \times 200} = 200\cdot111$$

$$s' = 200\cdot111 + \left(200\cdot111 \times 40 \times \frac{9\cdot56}{10^6}\right) = 200\cdot188$$

$$d' = \sqrt{\frac{3 \times 200 \times \cdot188}{8}} = 3\cdot75 \text{ or say 3 feet 9 inches.}$$

The side strain at the point of support is equal to $2a\text{P} = 77$ lbs.; and if we employ a wood pole of 6 inches diameter at the ground line and 5 inches diameter at the top, and standing 21 feet out of the ground, the pressure due to the wind on the pole itself will be $\cdot05p\text{D}'\text{L} = 116$. This pressure may be taken as if it acted at a point 10 feet above the ground, and the strain due to the wires as applied at a point say 20 feet above the ground.

The resultant bending moment $(77 \times 20) + (116 \times 10) = 2{,}700$ pounds at one foot, or somewhat less than that which the pole we are using can safely stand, which is equal to 15D^3 or 3,240 lbs. at one foot.

If now we increase the wind pressure to 50 lbs., and allow a factor of safety of 6, we get the following values:—

$$\text{P} = \cdot05 \times 50 \times \cdot192 = \cdot480 \therefore w = \sqrt{\text{P}^2 + \text{W}^2} = \cdot488$$

$$t = \frac{64000 \times \cdot0228}{6} = 244.$$

These figures give a dip of about 10 feet for a span of 200 feet, which is more than can generally be allowed at minimum temperature. We must then shorten the

span, and if we assume a dip of 5 feet, we get for the maximum span, $a = \sqrt{\frac{8 \times 5 \times 244}{\cdot 488}} = 141$ feet.

The side pressure at the point of support $= 2aP = 2 \times 141 \times \cdot 480 = 135$ pounds, which gives a bending moment of 2,700 at the ground line. The 6-inch pole will not be strong enough, especially as we have to allow a factor of safety of 6, which reduces the safe bending moment to $10\,D^3$ instead of $15\,D^3$; and we shall find that the pole must have a diameter of about 9 inches, which safely allows of a bending moment of 7290. The pressure of the wind on the pole itself will be $\cdot 05 \times 50 \times D' \times L = 420$, and the resultant bending moment will be $(135 \times 20) + (420 \times 10) = 6900$.

Cable line of two conductors, each of 7 strands of No. 16 L.S.G., insulated and braided to a diameter of ·430, and without bearer wires. Wind pressure 20 pounds per square foot. $W = \cdot 158, P = \cdot 430, w = \cdot 458, t = 365$. In this case we shall again find that for a span of 200 feet the dip will be considerably over 5 feet; so we will find the maximum span for this dip, which is $a = \sqrt{\frac{8 \times 5 \times 365}{\cdot 458}} = 178$ feet.

The side pressure at the point of support $= 2aP = 2 \times 178 \times \cdot 430 = 153$ lbs., which gives a bending moment of 3060. A $6\frac{3}{4}$-inch pole will be required, which will allow of a bending moment of 4612, and will add one, due to the pressure of the wind on itself, of $10(\cdot 05 \times 20 \times D'L) = 1230$, giving a total bending moment of $3060 + 1230 = 4290$.

For a similar line, when the wind pressure is 50 lbs. per square foot, and the factor of safety 6, we get $W = \cdot 158$, $P = 1\cdot 075$, $w = 1\cdot 09$, $t = 244$, and a dip of 5 feet will only allow of a span

$$a = \sqrt{\frac{8 \times 5 \times 244}{1\cdot 09}} = 95 \text{ feet.}$$

The side pressure at the point of support $=2a\text{P}$ $=2\times 95\times 1{\cdot}075=204$, which gives a bending moment of 4080. A $9\frac{1}{2}$-inch pole will be required, which will allow of a bending moment of 8573, and will itself add one of about 4300, so that the total bending moment will be 8380.

Cable line as above on housetops, and with bearer wires of 7 strands of No. 14 steel wire. For the cable $\text{W}=\cdot 158$, $\text{P}=\cdot 430$, and for the bearer wire $\text{W}'=\cdot 121$, $\text{P}'=\cdot 240$, $t=22500\times\cdot 0357=800$. The resultant pressure on the bearer wire is $w=\sqrt{(\text{W}+\text{W}')^2+(\text{P}+\text{P}')^2}$ $=\cdot 726$, therefore for a span of 200 feet

$$d=\frac{(200)^2\times\cdot 726}{8\times 800}=4{\cdot}54\text{ feet.}$$

The side pressure at the point of support $=2a\,(\text{P}+\text{P}')$ $=400\times\cdot 670=268$. In this case we do not need to use a pole of sufficient strength to stand the strain by itself, as stay wires must be used; and we may therefore suppose that a pole 15 feet long over all, and $3\frac{1}{2}$ inches external diameter, is used; and also that the resultant pressure acts at a point one foot from the top, and that the stay wires are attached a foot below this. The pressure of the wind on this pole will be $(\cdot 05\times 20\times 3{\cdot}5\times 15)=52{\cdot}5$ lbs., acting at a point $7{\cdot}5$ feet from the heel of the pole, and the resultant pressure at the point of attachment of the stay wire will be $\left(\frac{268\times 14}{13}+\frac{52{\cdot}5\times 7{\cdot}5}{13}\right)=318$ lbs.

If the stay wire makes an angle of 45° with the pole, the tension in it will be $\frac{318}{\sin\ 45^\circ}=450$ lbs., which will require a wire of 7 strands of No. 16.

The weight to be carried by the roof is the sum of the weights of the span of double line, the pole and saddle, and the vertical component of the

tension in the stay wire. The weight of the line is $2a(W+W')=112$ lbs., and that of the pole and saddle about 180 lbs.; and the vertical component of the tension in the stay wire $=450 \cos 45° = 318$, giving a total of 610 lbs.

For a similar line when the wind pressure is 50 lbs. and the factor of safety 6, we get $W = \cdot158$, $P = 1\cdot075$, $W' = \cdot121$, $P' = \cdot600$, $t = 535$, $w = 1\cdot7$. With a dip of 5 feet $a = \sqrt{\dfrac{8 \times 5 \times 535}{1\cdot7}} = 112$ feet. The side pressure on the line $= 2a\ (P+P') = 224 \times 1\cdot675 = 375$ lbs. and that on the pole $= 131$ lbs., giving a resultant pressure at the point of attachment of the stay equal to $\dfrac{(375 \times 14) + (131 \times 7\cdot5)}{13} = 479$ lbs.

The tension in the stay wire $= \dfrac{479}{\sin 45} = 677$ lbs. which will require a wire of 19 strands of No. 17. The weight to be carried by the roof $= 63 + 180 + 479 = 722$ lbs.

If it were necessary to use a span of 200 feet with a dip of 5 feet a very large bearer wire would be required, as the values of W' and P', and consequently that of w, increase with the size of the bearer. The actual wire required would be 19 strands of No. 12, for which $W' = \cdot561$, $P' = 1\cdot300$, and $t = 2480$. This would give $w = 2\cdot48$, and therefore if $a = 200$, $d = \dfrac{(200)^2 \times 2\cdot48}{8 \times 2480} = 5$ feet. Such a line is altogether impracticable, as the pressure on the roof and the pull on the stay wires would be so great that there would be much difficulty in finding suitable places to fix the poles. The tension in the stay wire would be about 1,480 lbs., and the downward pressure due to it would be 1,050 lbs. The weight of the line would be 288 lbs.,

which, with that of the pole and saddle, would bring the total pressure on the roof up to about 1,600 lbs.

We see from these examples how great a difference is made by a change from 20 to 50 pounds per square foot for the wind pressure; and although the extra cost of the line should not deter any one from fixing it, if there is any probability of such a pressure being brought to bear on it, yet the enforcing of this specification appears to be unnecessary, as it is doubtful whether a pressure even approaching to 50 lbs. per square foot has ever been registered in any of our large towns, and it is pretty certain that there is hardly a roof in London that has been designed to stand such a wind pressure. Mr. Preece, in a paper "On the Strength of Round Timber," read at the meeting of the British Association in 1885, stated that the experience of the Post Office showed that a fair average figure for the wind pressure was 18·75 lbs. per square foot; and many overhead electric light lines, which have been in use for some years without suffering, even at times when the telegraph and telephone wires have been blown down, have apparently been calculated for 20 lbs. wind pressure.

CHAPTER XIV.

Underground Lines.—Bare Wire Mains.—Built-in System.—Drawing-in System.—Conduits.—Brick and Concrete Culverts.—Earthenware Conduits.—Iron Pipes and Troughs.—Bitumen Concrete Conduits.—Wood Conduits.—Manholes.—Joint Boxes.—Method of Laying Cables.—General Arrangement of Mains.

ALTHOUGH overhead wires may often be used with advantage, more especially for the transmission of electricity over long distances; it will be found that, as a general rule, the use of an underground main is more satisfactory for the distribution of the current; and in England it is the only method which is allowed in any of the large towns. As with overhead wires, the insulation may be provided by supporting a bare conductor on glass or porcelain insulators, or by entirely covering the conductor along its whole length with insulating material; the former method being only employed with low pressures, and the latter with both low and high pressures.

In all bare wire systems a culvert must be constructed in such a manner as to keep out water as much as possible; and, as it is impossible to do this entirely, provision must be made, by connecting the culvert with the drains, for carrying off any water that may collect in it. In this culvert, insulators of porcelain or glass are fixed at regular intervals, and on them are supported the conductors, which consist of bare copper strips.

The advantages claimed for this method of insulation are, that the sectional area of the conductor may be increased within wide limits, without at the same time

materially increasing the cost of insulation; that the materials employed are not liable to much depreciation; and that connections between feeders and distributing mains, and between these latter and the house service wires, can be easily made, since the joints are only copper joints and have not to be insulated. The disadvantages are that the first cost of the culvert is considerable, and for small sectional areas of copper out of all proportion to the cost of the copper; that the culvert occupies a much larger space under the footways than can in very many cases be devoted to electrical mains, and this necessitates the use of continuously insulated cables alternating with lengths of bare strip; that the insulation resistance of such a system is by no means high, and is liable to considerable variation; and that there is always the unpleasant prospect of a serious breakdown, should the culverts get flooded by the bursting of a drain or water main.

As regards economy, both in first cost and cost of up-keep, too much has sometimes been claimed for bare wires underground; as, although they are decidedly cheaper to lay down than insulated cables when the joint area of the conductors is very large, there is not much difference in cost between the two methods for the areas usually required for distributing mains. For up-keep, an annual charge of 1 per cent. has been proposed as an ample allowance for these mains, but this is considered by many engineers as much too little; and the bare wire culverts have so far been in use too short a time to allow of any estimate based on actual working expenses being made, so that authoritative figures cannot be yet supplied. The cleaning of insulators and replacing broken ones, and the keeping of the culvert in good repair and free from water, are items of expenditure which will probably

increase with time; and the localizing of faults and their removal, except when they can be burnt out by the leakage current, entails the opening up of the ground, frequently for a considerable distance.

The bare wire system is, however, very convenient for branching off service wires, and this tells very much in its favour; as also does the fact that many small faults may exist without interruption to the service, since the continued flow of the leakage current will often remove the fault instead of making it worse, as would be the case with an insulated cable. The loss of current may be considerable, and should be taken into account; but this is, in the opinion of the advocates of the system; far more than counterbalanced by the conveniences mentioned above. The possibility of the culvert being flooded is one of the most serious objections to the system, and that this is a real risk is shown by the fact that an accident of this kind has occurred to the mains of the House-to-House Co. at Kensington, through a water pipe bursting in a street through which their mains were laid. In this particular case no interruption of the service resulted, because the mains consisted of well-insulated cables laid in iron pipes; but had there been a culvert with bare copper in place of this, a serious breakdown must have occurred, which would not, in all probability, have been a local one only, as the culvert would have acted as a convenient drain for the water to run into, and would have been flooded for some considerable length. Such an occurrence fortunately does not happen often, but the risk is somewhat similar to that to which overhead lines are subject from heavy snow-storms or gales; and, as the inconvenience to the users of the current would be more felt than when the telegraph lines are interrupted, it is all the more incumbent on

the supply companies to avoid the chance of an interruption from such a cause.

When continuously insulated conductors are used, they may be laid in various ways, all of which, however, can be grouped into two classes; in one, the insulated conductor is built in, that is to say, is laid in such a manner that access to it can only be got by opening up the ground; and in the other, the cable is drawn into a pipe or conduit, from which it can also be withdrawn if necessary. When the built-in system is employed, the mechanical protection of the insulated conductor may be provided by iron or steel tubes, as in the Edison or Ferranti mains, or by an armouring of iron wires or tapes laid up round the core, a method of affording protection which may be used with any class of cable.

The tubes or armoured cables are often laid direct in the ground, with a board or metal plate placed some few inches above them, to give warning of their presence to workmen who may have occasion to open up the ground for any purpose; or they may be laid in a boxing filled in with cement or asphalte. Another plan which is often employed is to lay the cables on bridges of wood in an iron trough, which is afterwards filled up solid with bituminous or other similar compound. In any case the cable must be laid in whilst the ground is open, which is often inconvenient; as the length of trench, which can be kept open at any given time, is restricted by the vestries or other road authorities. The cable on its drum is generally mounted on a trolly, which is wheeled along by the side of the trench, and as the cable pays off the drum, it is laid in place in the trench.

In the drawing-in system, the mechanical protection of the cable is provided by the pipe or conduit into

which it is drawn; this pipe or conduit being laid underground, and the trench filled in again, before the laying of the cable is commenced. There is therefore no need for armouring, or other such protection on the cable itself; and, in comparing the costs of a built-in armoured cable with an unarmoured one drawn into a pipe, the heavier cost of the armoured cable will be found to go a good way towards paying the cost of the pipe. Of course, when the built-in cable is laid in an iron trough filled in with bituminous compound, there is practically no difference in cost of mechanical protection, between it and a cable drawn into a pipe or trough, and therefore the choice of systems may be decided entirely by considerations of convenience. From this point of view the drawing-in system is much to be preferred, since the cables can be drawn in or out without disturbing the surface of the road or pavement; whereas with a built-in cable, the ground must always be opened up, whenever it is desired to obtain access to the mains for repairs, or to increase the sectional area of the conductor. This opening up of the ground and making the surface good again is an important item in the cost of underground work, especially in towns, where expensive pavements, such as wood or asphalte, may have to be taken up and replaced, and the mains placed below the bed of concrete on which the wood blocks or asphalte are laid. This class of pavement is of course avoided wherever possible, and the mains laid under the footway, which is generally paved in London with York flags; but even with this pavement, which is about the cheapest we have to deal with, the expense of excavating, of temporarily replacing the flags, and of vestry charges for re-laying and for broken stones, will amount to four or five shillings per yard.

Let us consider the effect of this on the cost of increasing the area of the conductors to keep pace with an increasing demand for current. With a built-in system, unless we lay in the first instance conductors of sufficient area to meet the maximum possible demand, (and this would probably tie up more capital than could be afforded), we must incur the expense of opening up the ground at any time when we wish to extend; whereas, with a drawing-in system, additional cables may be drawn into the existing conduit, or the smaller cable may be withdrawn and replaced by a larger one, or, if spare pipes have been laid in the first instance, additional cables can be drawn in as the need for them arises. Now the extra cost of laying a 3-inch instead of a 2-inch pipe, or a 4-inch instead of a 3-inch pipe, that is to say in either case doubling the capacity of the conduit, is a shilling or less per yard for each way; so that for a three-wire system, with a separate way for each cable, the extra conduit space would only cost about two-thirds of the amount required for opening up the ground and making good again. With a two-wire system with both cables in the same pipe, an extra 3-inch pipe can be laid for about two shillings per yard, or a 4-inch for about three shillings; so that, when extensions are taken into account, there is really no economy gained by the use of a built-in system; whilst the convenience, both to the supply company and to the users of the streets, which results from its being unnecessary to disturb the surface, is very great.

In some cases when the ultimate maximum section of copper can be determined beforehand, and the cost of laying the larger cable on the built-in system is not much in excess of that of laying a smaller one on the drawing-in system, the former may appear more economical; but this state of affairs rarely exists except

with high-pressure cables, as the cost of those for low-pressure circuits is generally so great that the larger section of copper cannot be laid at once; indeed, in many cases, the interest on the extra capital, which is lying idle for some years, would pay the additional cost of the drawing-in system. With high-pressure systems, however, the cost of the cable is a much smaller percentage of the total cost of the main; and it may therefore be possible to lay an armoured cable in the ground direct, at the same cost as an unarmoured cable with half the weight of copper, if drawn into pipes. With high pressures, however, there is a greater chance of a fault in the cable, and it is therefore all the more necessary that provision should be made to give easy access to the mains for repairs. Now the localizing of a fault is not a very easy matter on electric light circuits, and it is difficult to place it within perhaps 20 yards or so; and, when this is the case, the built-in cable will have to be dug up for a considerable length, and examined until the fault is found; and this examination may necessitate the cutting of the metal sheathing, which very often does not show any external signs of damage. With a drawing-in system, if the fault is located within the same limits, the engineer knows that it is somewhere between two surface boxes, and he can therefore draw out the cable between these points, and replace it with a length of good cable; an operation which can be performed very quickly, and with the minimum of inconvenience to the traffic in the streets.

From what has been said above, we see that as a general rule the drawing-in system is preferable, since it affords facilities for increasing the weight of copper in the mains as the need for it arises, and for repairing or replacing faulty lengths of cable; and further, it

need cause no interference with the traffic, after the first opening up of the ground when the pipes or conduits are laid. It is no doubt dearer in first cost in some cases than the built-in system, but the difference with equal insulation of the cables is not great, and is probably more than counterbalanced by the saving in the cost of maintenance and extensions, which results from the greater accessibility of the mains.

Conduits for underground wires take many different forms, and may consist of concrete or cement lined brick culverts, metal or earthenware pipes or troughs, or casings made of prepared wood or of bitumen concrete. Brick or concrete culverts are but rarely used for cables, unless a number are to be run, as they are more expensive and occupy more space than many other conduits. They must be divided up by longitudinal partitions into separate and distinct ways, so as to prevent the several cables from crossing or fouling one another. They are, however, used in several of the bare wire systems; indeed, excepting the iron trough used by the St. James' and Pall Mall Company, there are no examples of bare wire work where brick or concrete trenches are not used.

Earthenware pipes or troughs have been tried in England, some of the earliest telegraph lines consisting of gutta percha covered wires laid in earthenware pipes, the joints of which were made with clay; but they have never met with much favour. The Lake conduit, however, has been extensively used by the United States Electric Light Company and others in America; it is made of the best stoneware vitrified and glazed, which offers a very hard and smooth surface. The conduit is generally made with a number of separate ways, each shaped so as to take two cables (Fig. 77), and is delivered in short lengths, which are connected by stoneware

covers set in cement. The great objections to the use of stoneware are its liability to fracture, and the difficulty of making good joints without making them so rigid that they will not adapt themselves to slight alterations of alignment due to the sinking of the ground or other causes. One of the troubles with the telegraph lines in which earthenware pipes with clay joints were used, was that roots of trees and other vegetation forced their way through the joints; and Mr. Fleetwood, in a paper read before the Society of Telegraph Engineers in 1887, mentions a case where a root forced its way in,

FIG. 77.

and entwined itself round the cable in such a way as to hold it fast and prevent it from being withdrawn. At Woking, the mains in connection with the central lighting station are laid in earthenware pipes, but these latter have not been in use long enough to say whether they will prove satisfactory in all respects, or not.

Metal pipes or troughs, either of cast or wrought iron, are largely employed, and in New York some zinc tubes laid in hydraulic cement have also been used. When laid direct in the ground, cast-iron pipes are preferable to any other; as they are very strong, and last much longer, when in contact with the soil, than wrought-iron

pipes, even if the latter are galvanized or served with jute soaked in bitumen. The experience of the Post Office Telegraph Department has led them to adopt cast-iron socket pipes as the best and most convenient conduit; and as they, and their predecessors, have had them in use for over forty years, and have also tried split pipes, wrought-iron pipes and earthenware pipes, their decision is one which must carry great weight. In America wrought-iron pipes are generally laid in groups, embedded in asphalte concrete, or hydraulic cement; and the grouping is altered to suit the space available, the pipes being laid, sometimes in two or three rows one above the other, at other times spread out into one wide row. Zinc pipes are sometimes used instead of the ordinary iron pipes, as also are pipes made of sheet iron lined with cement. The grouping of the pipes and laying them in concrete has the great disadvantage that more space is occupied underground, and that the system is not so flexible as one in which the pipes are all independent, and can be shifted nearer or further from one another to get past the various obstacles which are met with underground; but it makes a strong and lasting job, and has been found to make a good conduit as regards gas-tightness; a matter of the greatest importance in many American cities, where the soil is saturated with gas to a very considerable extent.

Instead of pipes, troughs of a flat U-shape may be used (Fig. 78), and these are convenient, in that a length of straight trough can easily be taken out, and a T-branch substituted for it, at any place where a service wire has to be connected; whereas a pipe must be broken before it can be removed. The flat trough, however, is not so strong as the pipe, and the same advantage as regards branches may be got by substituting a length of split pipe for the solid pipe, opposite each alternate party wall

of the houses, or by putting in at each of these places a split T-piece, the outlet for the branch being plugged up until required for use.

FIG. 78.

The Johnstone conduit (Fig. 79) is a cast-iron trough divided by vertical and horizontal partitions into six separate ways. It is made in lengths of about six feet, and arranged so that the cover can be removed, and access gained to the upper ways at any time. The idea

FIG. 79.

is, that the lower ways shall be used for feeders, or cables from which no branches are to be taken, and the upper ones for distributing mains; and, when a service wire is to be connected, the cover is removed from one length, and replaced by one fitted with a T-piece.

The Callender-Webber casing consists of blocks of bitumen concrete, with two or more separate ways running lengthwise of the blocks (Fig. 80); each way being intended to take one cable. The joints between the lengths of the casing are made in the following manner:—The two lengths being in position, a long mandril is pushed through each hole in the length last laid, and into the corresponding hole of the block to which it is to be joined; and hot bitumen is poured over the joint, and rammed down so as to fill up the space between the two blocks, except where it is

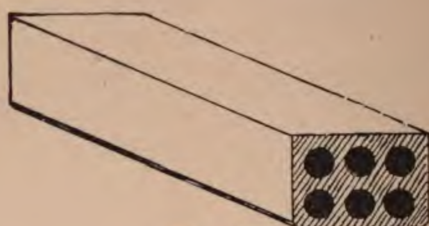

FIG. 80.

occupied by the mandrils. When the joint has cooled down, the mandrils are withdrawn, leaving smooth holes through the joint of the same diameter as the ways in each block. The casings are sometimes laid without further protection, and sometimes with an inverted iron trough placed over them so as to cover the top and sides, and protect them from injury from the picks of workmen.

The casing is strong enough to withstand any pressure to which it is likely to be subjected underground; a case being mentioned by General Webber, when replying to the discussion on his paper on the "Distribution of Electricity in Chelsea," where a steam

roller was at work, immediately after the casing had been laid about 30 inches under a Macadam road, and where the casing was therefore subjected to a good practical test, which it stood satisfactorily. At the same time General Webber stated that the material had the defect of being friable, and of not affording such good protection against injury as other forms of conduit when the ground about it was being excavated for any purpose, and further, that it was porous and susceptible to changes of temperature. Its porosity is of no great moment if a waterproof insulating covering is provided on the cable, as it always should be; but the softening at moderate temperatures is the cause of some inconvenience, since it is necessary to shift the cables periodically, as otherwise they adhere to the casing, and cannot be drawn out without considerable risk of injury.

A somewhat similar conduit is the Dorsett conduit, of which considerable lengths have been laid in America. The materials, of which the blocks are made, are coal tar pitch, and fine gravel; and the separate sections are jointed by inserting paper tubes which form sleeves connecting the ducts in the two lengths, and then pouring soft mastic in to fill the space between the lengths, and join them together. The reports of this conduit have not been favourable, as it is said to be porous, inelastic, and brittle; but many of the failures which are attributed to it, were due to the use of insulating materials on the cables which were not waterproof, so that the insulation in great measure depended on the ducts being kept dry.

Another conduit, which has been extensively used in America, is one composed of creosoted wood tubes, or blocks of wood of square section with a hole through them lengthwise. Several such tubes are placed to-

gether (Fig. 81) and enclosed in a creosoted wooden casing. The lengths are fitted together by turning a boss at one end of the tube, and recessing the other end, so as to make a cup for the boss to fit into as shown in Fig. 82. One great objection which has been urged against these conduits, is the destructive effect of the creosote on lead-covered cables, due to the chemi-

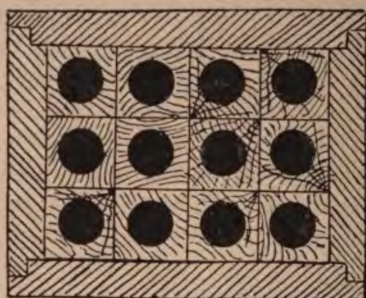

FIG. 81.

cal action which takes place between the lead and some acid which is set free from the creosote. Great trouble was experienced with cables encased in pure lead tubes, the lead becoming deeply pitted with holes; and the life of the cable was very short; but with tubes of lead

FIG. 82.

alloyed with a small percentage of tin, the corrosion is very much diminished, and the life of the cable correspondingly increased.

With few exceptions the conduits for drawing-in systems in England are of iron pipe, either cast or

wrought, or of Callender-Webber casing, the former being laid in the ground singly, and not embedded in concrete or grouped together in the American way. It appears to have been recognised that it is practically impossible to maintain any underground conduit dry, or gas tight; and that, when this is attempted, the result is generally that, although the water and gas cannot be kept out of the conduit, the latter is well enough made to retain them when once in. For this reason, in many cases, no attempt is made to get tight joints, but provision is made to facilitate the escape of either water or gas which may have entered; and for the rest, an insulated cable whose covering is waterproof is used, and no dependence is placed on the conduit, except as a mechanical protection. Looked at from this point of view the cast-iron socket pipe forms the most satisfactory conduit, as it affords the most perfect protection from mechanical injury, is very durable, occupies but little space, and is well adapted for use when obstacles are met with, as the alignment can easily be altered, more especially when the rubber ring joint is used instead of the lead joint.

A very important item in any system of conduits is the manholes, which should be made as large as possible, and placed at all corners, and at intervals of 60 to 100 yards in straight runs, according to the size of the cables. Where a number of cables are run together, or at places where branches are taken off in several directions, a brick manhole (Fig. 83) may be used, fitted with a cast-iron frame at the top, in which is seated the cover; this latter being also a cast-iron frame, filled in with material which corresponds with the surrounding pavement. A form of manhole or surface box very often used is a rectangular cast-iron box, (Fig. 84) with a cover as described above, and with outlets cast on it

corresponding to the number and positions of the pipes to which it is to be connected. These boxes are often

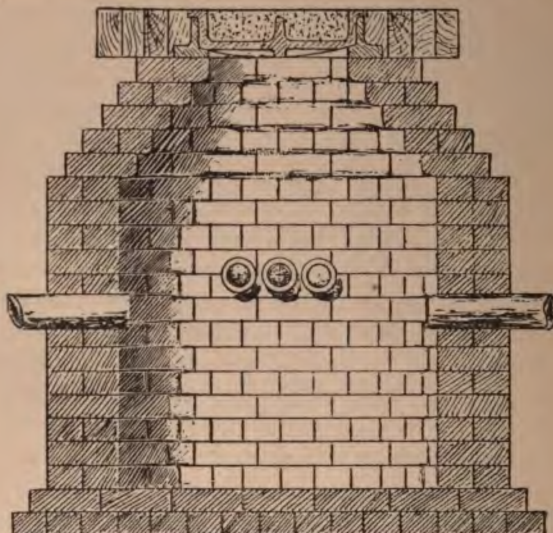

FIG. 83.

made without a bottom, or with a perforated bottom; and are set on rubble to facilitate the draining away of water which may collect in them from the

FIG. 84.

pipes, which latter, wherever possible, are laid with a slight dip towards the manholes. In addition to these

larger boxes, which are required for drawing the cable in or out, and in which the more important branches are jointed to the main cables, service boxes are required for house connections; and these may be similar boxes of smaller size, or split pipes (Fig. 85), and should be placed opposite every alternate party wall. In some low-pressure systems, the joints between the various lengths of cable, and between main and branch cables, are not soldered and covered with insulating material, but are made by clamping the conductors together; and, when

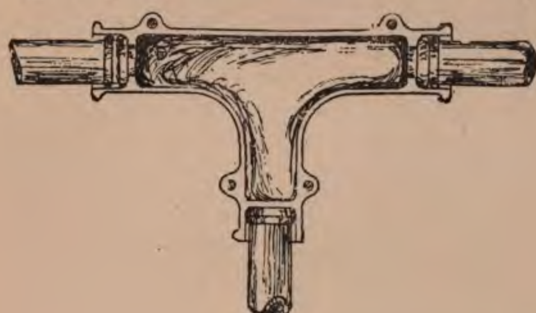

FIG. 85.

this is done, special boxes are provided, either filled with oil or other insulating compound, like the joint boxes described and illustrated in chapter X., or arranged with watertight lids and inlets, so as to exclude moisture as much as possible. Several types of surface and joint boxes, as used by the various Supply Companies, are described in the following chapter, in which particulars are given of the systems employed by many of them.

As the conduit is laid underground, a wire should be threaded through each duct, and left, with its ends made fast in the surface boxes, ready to be used for drawing in a hauling line; and the ducts themselves

should be examined to see that the insides are smooth, and that the ways are not blocked, as any obstruction left in them may be the cause of much trouble when the cables are being drawn in. If any obstruction is left in, or if a wire is broken in the conduit, rodding must be resorted to to clear away the block, or to thread a fresh wire through. For this, cane rods 4 to 6 feet long, and provided with screw ferrules at their ends, may be used; the rods being passed into the duct, and jointed together as they go in.

For drawing in the cables, the drums, on which they are coiled, are mounted on stands so that they are free to revolve; and these stands are fixed in any convenient position near the surface box, at which the cables are to enter the conduit. The end of the cable is attached by a strong but smooth fastening to a rope, and this rope is first pulled through the duct by means of the wire which had been left in it, and is then used to draw the cable through. In straight runs the length of cable that can be pulled through at one time depends on its weight, but in street work it is very seldom that this limit can be reached, owing to the frequent changes of direction of the conduit; and when the cable has been pulled through as far as it is thought advisable, or when there is any sharp bend in the conduit, it must be brought to the surface, and laid on the ground in long flakes. When sufficient cable to reach to the end of the run has been pulled through, the hauling rope is drawn through the next length of conduit, and the cable is pulled through in a similar manner.

When a long length of cable is being drawn in, the friction between it and the surface of the duct may be considerable; but this may be much reduced by lubricating it with soft soap, black lead, or whiting; and when this is done, and care has been taken to see that

the surface of the duct is smooth, and that there are no obstructions left in it, the cables can be pulled in without fear of damage.

With heavy cables, such as are required for low-pressure circuits, it is best to provide a separate way for each; but with the smaller cables generally used on high-pressure circuits, two may be drawn into the same duct, in which case they are both attached to the same hauling rope and drawn in together.

With regard to the general arrangement of the system of underground mains, means should be provided for disconnecting sections of them for testing purposes, or for making fresh service connections or repairs, without stopping the supply of current to the consumers; and it is therefore advisable, wherever possible, to loop the mains, so as to give two separate routes from the generating station to any point in them, and to arrange that they can be easily divided up into comparatively short sections. This subdivision of the mains is easily arranged on low-pressure circuits, where there is very little objection to bare clamped joints, if made in a suitable box underground; but the greater difficulty of preventing serious surface leakage, and the objections to the conductor being exposed, when high pressures are used, are strong arguments against any similar arrangement, and in favour of all parts of the high-pressure circuit which are underground being covered with a continuous coat of insulating material. For this reason we often find that on high-pressure circuits no provision is made for dividing up the mains; but there are some cases in which this is done, such as the circuits of the Metropolitan Electric Supply Company; and we shall therefore return to this point again when describing the arrangement of their mains.

CHAPTER XV.

Underground Mains of the Westminster Company.—Crompton Culvert.—Kennedy Culvert.—Insulated Cables.—The St. James' and Pall Mall Company.—The Chelsea Supply Company. — The Liverpool Supply Company. — Bradford. — Berlin.— Paris. — Edison System. — The London Electric Supply Company.—The Metropolitan Electric Supply Company.—The House-to-House Electric Light Company. — Hastings.—Eastbourne.—Overhead Wires at Reading and Exeter. — Continental High Pressure Circuits. — Underground Mains at Chicago.—The Westinghouse Company.— The Thomson Houston Company.

Within the last three or four years, a large number of central electric lighting stations have been put into operation; and in connection with one or other of these stations, most of the systems of underground and overhead mains that have been described, have been put to the test of practical working. It is proposed, therefore, to describe the particular methods employed in some of these installations, first taking those which employ low-pressure direct currents, and then those using high-pressure currents with transformers.

The distribution of low-pressure currents is in all cases effected by means of underground mains, as the weight of the cables required for the heavy currents would make the erection of overhead lines both difficult and costly; and further, various methods can be employed with a view to lessening the cost of these underground mains, which would not be permissible where high pressures are used. The most prominent example of these, is that in which bare copper strip supported on insulators is laid in a culvert, and of this system there are several types in use now in London.

THE WESTMINSTER ELECTRIC SUPPLY CORPORATION.

The underground mains of this company may be taken first, as in their network will be found examples of each of the three most important methods which are now employed, viz.:—bare copper strip, continuously insulated conductors drawn into conduits, and continuously insulated conductors built in. The current is distributed on the three-wire system at low pressure from the generating stations, and from distributing centres; at which are placed batteries of accumulators, which are connected to the generating machinery by two wire feeding mains. Wherever it has been possible to find sufficient space for the culverts required for the bare wire system, this method of laying the conductors has been employed; and when space has not been available, continuously insulated cables have been laid, either on a drawing-in or a built-in system.

Two bare wire systems are in use, the mains which were first put underground being laid in culverts on the system introduced by Messrs. Crompton & Co.; whilst those of later date have been laid on a system devised by Prof. Kennedy, the Engineer of the Company. The Crompton culvert consists of a concrete trench built under the footway, in which, at intervals of from 10 to 20 yards, are set glass insulators on which the copper strips are carried. Figs. 86 and 87 show respectively a cross-section and a longitudinal section of an ordinary three-wire culvert, the inside dimensions of which are 15 inches wide by 12 inches deep, whilst the outside dimensions are about 29 inches by 21 inches. The insulators are carried on stout oak crossbars (which are built into the concrete so as to leave a clear space of a couple of inches or so between their under sides and the floor of the culvert); and they

are made with a number of corrugations on their outer surface, so as to increase the resistance to leakage; and with a deep notch on the top which forms a recess in which the conductors rest. The conductors consist of one or more strips of copper, 1 inch wide by $\frac{1}{4}$ inch thick, according to the current to be carried, and are laid flatways in the recess in the insulators. As the distance between the insulators is considerable, the

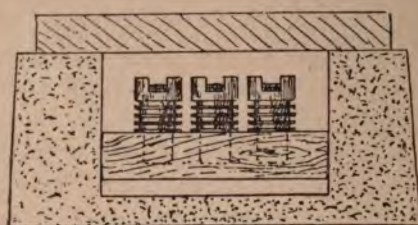

FIG. 86.

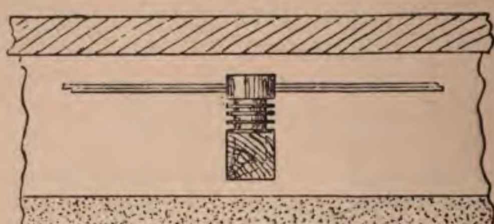

FIG. 87.

tendency of the copper strips to sag down between the supports has to be counteracted by straining the strips; and therefore, straining boxes are placed at intervals depending on the length in which the strips can be delivered, or on the length of the culvert which can be built in a straight run. At these boxes two oak bars, of a larger cross-section, are built in across the end of the culvert, and to them are fixed insulators placed horizontally, as shown in Figs. 88 and 89; one

insulator being provided on each crossbar for each line of conductor. Each of these pairs of insulators supports a gun-metal bridge, having a rectangular hole through which the conductor passes, and in which it can be securely clamped by means of two set-screws.

The method of laying a section of main is to pass the copper strips into the culvert, place them in the notches in the insulators, and pass them through

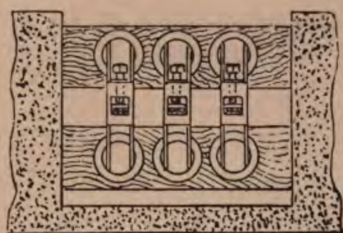

FIG. 88.

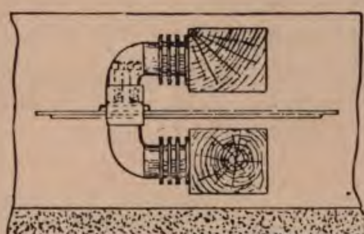

FIG. 89.

the holes in the gun-metal bridges. One end is then made fast by tightening up the set-screws in the bridge, and a tensile strain is put on the other end by means of a screw-tightening gear; and, when the strip is sufficiently strained, the set-screws in the bridge are tightened up, thus holding it securely in place. The culvert is covered by flagstones, and over the top of these stones the ordinary paving is relaid. At each

set of insulators a manhole cover is provided, so as to give access to them; and these manholes are used as service boxes, from which the house connections are taken. Similar culverts, but of greater width, are used for accommodating a three-wire distributing main and a two-wire feeding main, or two three-wire mains may be laid side by side; the arrangement of insulators, etc., being the same in each case except as regards the number fixed on each crossbar.

The Kennedy culvert system differs from the one

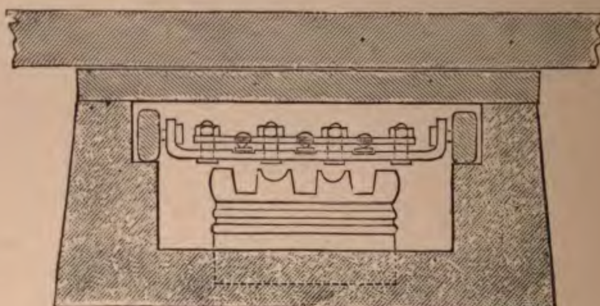

Fig. 90.

just described, in that it has been specially designed with a view to facilitate the drawing in of the conductors, after the culvert is completed and covered in, and that the straining gear has been rendered unnecessary by placing the insulators at much shorter intervals. This arrangement simplifies the operation of laying the mains very considerably; but it has of course the disadvantage that, owing to the larger number of insulators, there must be a correspondingly greater chance of surface leakage. The culvert is built of concrete, and two sizes are generally employed, one to carry a three-wire distributing main (Fig. 90), being 15 inches

wide by $7\frac{1}{2}$ inches deep, inside measurement; and the other (Fig. 91) to carry a three-wire distributing and a two-wire feeding main, being 20 inches wide and the same depth. The space occupied by these culverts

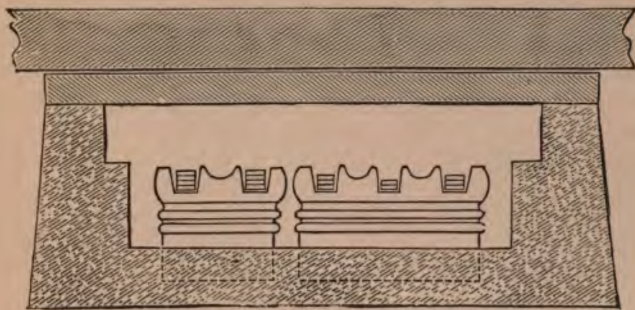

FIG. 91.

underground is 26 inches and 31 inches respectively in width by 12 inches in depth. The concrete is shaped as shown in the figures by means of templates, the culvert being wider inside at the top than at the bottom, so as to form a ledge on each side, and thus

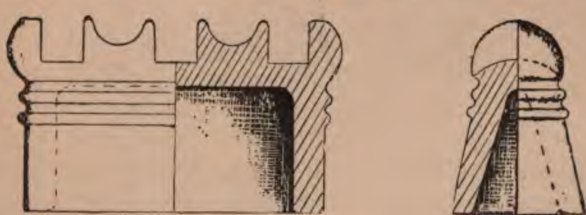

FIG. 92.

provide a pair of rails on which the drawing-in trolley can run.

At intervals of 6 feet, hollow stoneware insulators (Fig. 92) are embedded in the concrete floor of the culvert, these insulators being moulded with several

corrugations to increase the length over which surface leakage must take place, and with deep slots in which the copper strips can lie. The drawing-in trolley, shown in position in Fig. 90, consists of a bent iron plate supported on four teak wheels, which run on the ledges provided on the sides of the culvert; in this plate notches are made corresponding in position to the slots in the insulators, and in these notches the

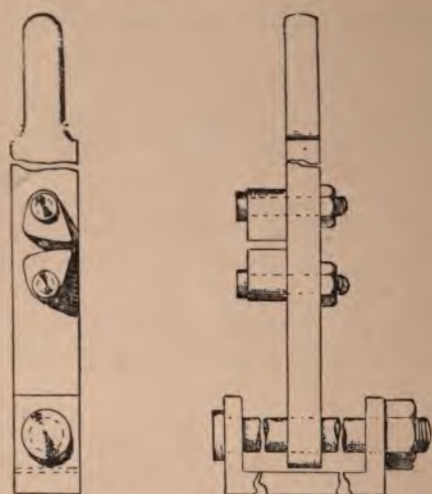

FIG. 93.

copper strips are laid. A cover plate is provided in which are fixed pointed steel set-screws, which can be jammed down on the copper strips by bolts which pass through both plates.

When a conductor is to be drawn into a completed culvert, it is first laid out on the pavement, and straightened by means of a special tool (Fig. 93), which consists of a lever, turning on a bolt in a frame which can be fixed to the ground; to this lever are

attached two cams with milled edges, which are free to turn on studs screwed into the lever; between these cams the copper strip is held tightly, and a considerable strain is put on the strip by pulling the lever over. The strip is then clamped in position between the plates of the trolley, so that it will be led fairly over the slots in the insulators in which it is to lie; and the trolley is hauled through the culvert by means of a rope previously drawn through. This method of drawing in the conductors has been found very convenient, as it does away with the necessity for the numerous surface boxes required in other systems, and thus renders it possible to place the culvert under the

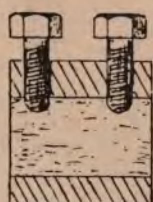

FIG. 94.

roadway, when this is a more convenient position than under the footway.

The copper strips are 1 inch by ¼ inch, and can be obtained in lengths of about 50 to 60 yards; the various lengths of strip are joined at the manholes by tinning the ends and clamping them together in a metal connector (Fig. 94).

Owing to the large amount of space occupied by these concrete culverts, it is frequently impossible to find room for them, and when this is the case continuously insulated cables are employed. In some few cases, lead-covered and armoured jute cables, laid in the ground with a board placed over them to give

warning of their presence, have been used for feeders; but, with these exceptions, the cables used by the Westminster Company are insulated with vulcanized indiarubber, and are drawn either into bitumen casing or into iron pipes. The connection between a cable and the copper strip (Fig. 95) is made by sweating on to the conductor of the cable a lug having a projecting tongue, and clamping this tongue and the copper strip together, in a connector like that shown in Fig. 94.

Wherever possible, the distributing mains are under the footway, and service boxes are placed opposite

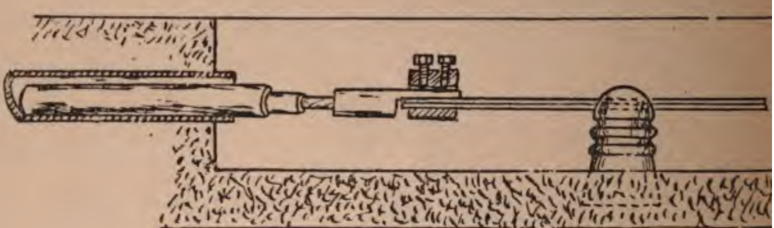

FIG. 95.

every other party wall; the house connections being made with vulcanized rubber cables laid in iron pipes.

The Crompton system was first used by the Kensington and Knightsbridge Electric Lighting Company, who employ a three-wire low-pressure system of distribution with accumulators, and it has also been laid down by Messrs. Crompton for the Notting Hill Electric Lighting Company, and at Birmingham and Northampton; in all cases, however, it has to be supplemented by insulated cables, owing to the difficulty of finding room under the footway for the culvert. In most cases the cables used are insulated with vulcanized rubber, and drawn into iron pipes; though other cables, such as the bitite cables, have also been laid.

The St. James' and Pall Mall Electric Light Company.

This company distributes electricity at low pressure on a three-wire system, and is especially fortunate in having to supply a district, in which the demand for current in premises within a quarter of a mile of the station is sufficient to require practically all that can be produced. The system of distribution employed differs from those just mentioned in that no accumulators are used, and that the feeders all feed into a ring main from which the district outside it is

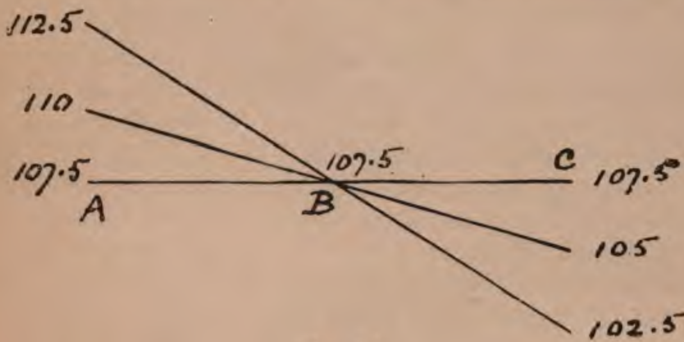

Fig. 96.

supplied. There are six feeding mains which connect the ring main to the station, and at each of the six points of connection the pressure is maintained constant; the pressure rising between the feeding point and the station and falling, between it and the most distant house connections, as shown in Fig. 96, where A represents the station, B a feeding point, and C the farthest house connection. At no load the pressure is the same at all three points; at half load it rises to 110 volts in each half of the three-wire main at the station

end, and falls to 105 at the lamp end; and at full load it rises to 112·5 volts at the station, and falls to 102·5 at the lamps. There is thus a maximum fall of pressure between A and C of 10 volts, and a variation at any given point of nearly 2½ per cent. each way from the mean value. Lamps inside the ring main are supplied direct from the feeder mains, and are of higher voltage than those used in the outer district, the voltage being chosen to suit the mean pressure at each point of supply.

The mains consist of strips of bare copper 2 inches by $\frac{1}{10}$th of an inch, set edgeways in slots in porcelain bridges fixed in an iron trough. One or more strips are placed in each slot according to the sectional area required, the usual sizes being 1·6, 0·8, and 0·4 square inch section for the outside conductors, and half these areas for the middle conductors; thus giving a joint area of 4 square inches in the largest size, and of 2 square inches and 1 square inch respectively for the two smaller sizes. The cast-iron troughs, a longitudinal and a cross section of which are shown in Figs. 97 and 98, are made in lengths of 3 or 6 feet, and are jointed by trough-shaped pieces, about 6 inches long, which enclose the iron trough; the joint being made water-tight by running in lead. The troughs are laid wherever possible with a slight fall towards the junction boxes, and the porcelain bridges are so shaped as to allow a free passage to any water which may get into the trough. The junction boxes are connected to the drains, and when a dip occurs which cannot be drained direct, arrangements are made to siphon out the water. Between the porcelain bridges on which the copper strips rest, are placed porcelain saddles, which hold the strips in place, and prevent any chance of contact between them. The trough is closed by a cast-iron

cover which rests on a ledge cast on each side in the trough, and the joint between them is made tight with red lead and yarn. Junction boxes of brick are provided about every 100 feet or so, and in these provision is made for disconnecting the mains, for testing and other purposes. When a main which is in circuit is

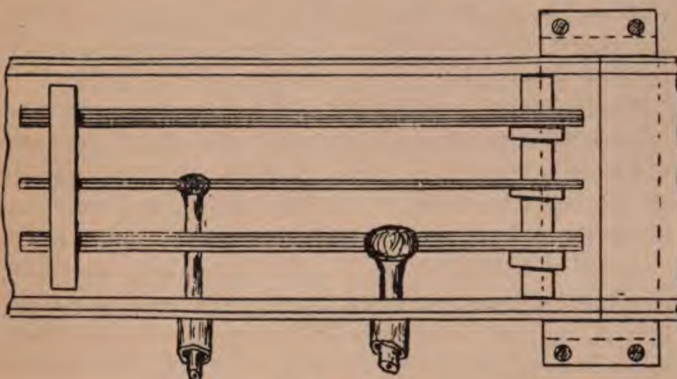

FIG. 97.

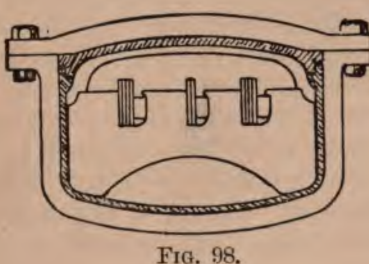

FIG. 98.

to be broken, the junction is first short-circuited by a piece of insulated cable terminating at each end in a copper clip, which is pulled off again after the copper strips have been disconnected. House services are made with rubber cables laid in wrought iron pipes,

these latter being screwed into bosses cast on the trough, and the cable being soldered to the main conductors.

Owing to the arrangement of the mains in a continuous ring, fed at six different points, each customer can be supplied by more than one route from the station; and therefore any section of the main can be cut out of circuit for testing, repairs, or making fresh house connections, without interfering with the supply of current to any other part of the system.

This cast-iron culvert has the advantage that it takes up much less space than any of the concrete ones, the trough being only about 11 inches by 7 inches, and it has therefore been found possible to use the bare strip throughout for the distributing mains; but it is essentially a built-in system of mains, and access to it, for making connections or repairs, can only be got by digging up the trough and breaking the cover joints.

The Chelsea Electricity Supply Company.

The system employed by this company is a transformer system with accumulators, which are charged in series and discharged in parallel. In addition to the generating station there are three sub-stations, in each of which is placed a double battery of accumulators, one half of which is always connected to the distributing main, whilst the other half batteries in each station are connected in series in the charging main. At the hours when the demand for current is greatest, both half-batteries are connected in parallel and discharge into the distributing network; and the generating plant is used to operate continuous current transformers, whose secondary circuits are also connected to the distributing network. When the batteries are charged and the demand is small, the gener-

ating plant is stopped. The secondary distribution is effected on the two-wire system, a number of feeders running from each sub-station to distributing points, from which the network proper branches out. The cables employed in this installation are insulated with bitite, and are drawn into Callender-Webber casing, in connection with which manholes and joint-boxes are provided as required to facilitate the drawing in or out of the cables, and the connecting of branches.

The same system of underground mains is used by the Metropolitan Company for the low-pressure distribution from their Whitehall station, except in Northumberland Avenue, where the cables are laid in the subway; and also by the Electricity Supply Corporation, this latter company taking the additional precaution of placing an inverted iron trough over the bitumen casing, to protect it at the top and sides from mechanical injury.

The Liverpool Electric Supply Company work at low pressure on a two-wire system from three generating stations, and use either lead-covered jute cables or bitite cables laid on a built-in system. The cables are laid in cast-iron troughs with socket joints, into which there is first run a layer of molten bitumen, which covers the bottom of the trough to a depth of about $\frac{1}{4}$ inch. Before this bitumen sets, wooden bridges are placed in it about 18 inches apart, and on these bridges the cables are supported. Bitumen is run into the trough so as to cover the cables and fill it nearly to the top, and a cast-iron cover is then fitted on; or sometimes a layer of cement concrete is used to finish with, in which case the iron cover is not needed. Some of the smaller cables are lead-covered, and are laid in grooved wood casing filled in with bitumen. The connections between the feeding and distributing

mains are made in cast-iron boxes, fitted with socket pieces to receive the ends of the cast-iron troughs; the box is laid below the level of the pavement, so that it has a cover independent of the surface plate, which is flush with the pavement. The box cover is held down by a crossbar and central bolt and the joint between it and the box is made tight by an india-rubber washer. The connections are made inside this box by sweating copper lugs on to the ends of the cable, and bolting them to copper connecting bars, which in some cases have terminals fitted to them so that a fusible cut-out can be inserted in the branch.

The Bradford central station also distributes current at low pressure on a two-wire system, the mains consisting of lead-covered jute cables, armoured with two layers of iron strip, and served outside with compounded jute. These cables, except at road crossings, and other places where extra protection is provided, are laid direct in the ground, the joints in the cables themselves being made by clamps in cast-iron boxes filled with a heavy insulating oil. The joints between feeding and distributing mains are made in cast-iron boxes fitted with terminals to which the several cables are attached, the covers and inlets for the cables being arranged so as to be as nearly watertight as possible.

The largest low-pressure system on the Continent is that at Berlin, where current is supplied from several stations to a network of underground mains. In this system, which was originally a two-wire system, a very large amount of copper was put down in feeders, some of which were over 1,000 yards in length; but owing to the large number of feeding points, it has been possible to keep the variation of pressure in the distributing mains down to as low a figure as $1\frac{1}{2}$ per cent. The cables are lead-covered jute and armoured, and are

laid under the footways generally without the further protection of casing; the joints are made with clamps, and enclosed in cast-iron boxes filled with insulating oil. In some later extensions the three-wire system has been employed, with a view to reducing the weight of copper required; the cost of the two wire mains as originally arranged being very heavy.

In Paris a very large amount of underground mains has recently been laid by the various companies who have obtained concessions for the lighting of the city, and very different methods have been adopted for insulating and protecting the conductors. The Popp Company are working on a system, in which several stations deliver current into a system of charging mains, which supply accumulator stations in series; these sub-stations supplying the current to a low-pressure network of distributing mains. The charging mains are insulated with vulcanized india rubber, lead covered, and served with compounded hemp, as also are some of the low pressure mains; but in many cases these latter consist of bare copper. The cables are laid in cast-iron troughs in which are placed grooved wood casings saturated with paraffin, several layers of these casings being often placed one above the other. The bare conductors consist of uninsulated stranded cables, held by split porcelain bushes supported in blocks of oak, which are generally fixed in the cast-iron troughs above the casings containing the insulated cables. At intervals of about 100 feet or so, manholes are provided to give access to the mains; and service boxes are laid opposite the houses requiring a supply, in which the connection is made between the main and branch conductors by means of clamped joints which are left uninsulated.

The Place Clichy Company supplies current by

means of two-wire feeders and five-wire distributing mains, with accumulators or dynamo regulators placed at the distributing points to equalize the pressure in the four distributing circuits, as described in chapter IV. The mains consist of jute cables, lead-covered and armoured, and are laid in the ground direct, a strip of galvanized iron wire gauze being laid over them, to give warning of their presence to workmen who may be opening up the ground. The joints are made by fitting brass lugs to the ends of the cables, and bolting these lugs together; and the exposed parts of the jute covering are protected from moisture by enclosing them in rubber sleeves, bound round with galvanized iron wires. The joint is enclosed in a cast-iron box filled in with melted asphalte. At intervals where important junctions are made, distributing boxes are used in which the joints are made by removable copper connecting pieces or by lead fuses.

The Société d'Eclairage et de Force distribute current on a two-wire low-pressure system, with batteries of accumulators at the stations and at various sub-stations. The mains consist of uninsulated stranded cables, or of bare copper strips, supported on insulators placed at intervals of about 10 feet in cement culverts. The insulators for the cables are of porcelain of the double-bell pattern, cemented to galvanized iron standards, and have a semi-circular groove at the top to receive the copper strand, which is held in place, after being strained tight, by means of iron stirrups passing over the cable and under projecting lugs on the insulators. The insulators for the copper strip are very similar, but instead of the semi-circular groove, there is a deep slot provided for the strips to rest in. Joints in the cables are made by splicing and soldering the two ends together; and the strips are connected by being

clamped between iron plates bolted together, the joint being made solid by running in solder.

The Edison Company, distributing current on the three-wire system, use bare stranded cables supported on insulators at intervals of about 6 or 7 feet. These insulators are of the double-bell pattern, and are fitted with cups of galvanized cast iron, in which is a deep slot in which the cables are laid one above the other. These cups have projecting lugs, which serve as supports for the iron stirrups which pass round them and the cables, and keep the latter in place after they have been strained. The insulators are fixed in cement culverts about 14 inches deep, and varying in width from 10 to 16 inches, according to the number of insulators. The service wires are lead-covered cables laid in iron pipes, and are connected to the main conductors by iron straps clamped together with screws and afterwards run in with solder.

In America, the majority of the low-pressure work has been done by the Edison Company, or by local companies formed to work their system. In most cases the mains consist of Edison tubes arranged for a three-wire distribution, made and jointed in the manner described in chapter X., but several of the local companies use continuously insulated cables instead of the tubes. Since its first introduction, there have been many improvements made in the Edison underground system, not only in the details of the tubes themselves and of the joint boxes, but also in the design of distributing boxes and junction boxes. These boxes are specially designed so as to afford facilities for breaking up long mains into comparatively short sections, as an aid to localizing faults. They are made of cast iron with double covers, the inner one being made water-tight by a rubber gasket; and contain insulated blocks

to which the ends of the conductors are connected; the junctions between these blocks, required to complete the continuity of the circuit, being made by means of removable copper strips. When the feeders are of considerable length, as is often the case, several of these boxes are inserted, to divide them up into sections; and where more than one feeder main passes through the box, provision is made for cross connections, so that if one section of a feeder is faulty, it is not necessary to cut out of circuit the whole length, but only the bad section, the remaining feeders in this section being connected up to carry the whole current.

The London Electric Supply Corporation.

This company's system differs from all others at present in use in England, in that an extra high pressure is employed, with a double transformation between the generating station and the lamps. According to the original design, the current which is generated at Deptford is to be conveyed at a pressure of 10,000 volts to four transformer stations at Blackfriars, Pimlico, Bond Street, and Trafalgar Square, and distributed from these stations at 2,400 volts to a number of transformers, from which the consumers' premises are to be served by means of low-pressure distributing networks. At present this plan has not been carried out fully, owing to the fact that the houses taking current are too much scattered, and there are therefore only three or four cases in which a low-pressure distributing network is employed, the general plan being to fix the 2,400 to 100 volt transformer on the consumer's premises; but it is intended, as the demand increases, to arrange for sub-stations, each of which will serve by low-pressure mains the houses in the immediate neighbourhood. The complete system of mains, etc., will

then be as shown in Fig. 99, where A is the dynamo machine at Deptford, B is one of the four main transformer stations, C a transformer sub-station, H, H, H, consumers' premises, E, E, E, earth connections, and S.D. safety devices. The 10,000 and 2,400 volt mains are concentric, and, for the reasons mentioned in a preceding chapter, the outer conductor of each is connected permanently to the earth, the one at the dynamo

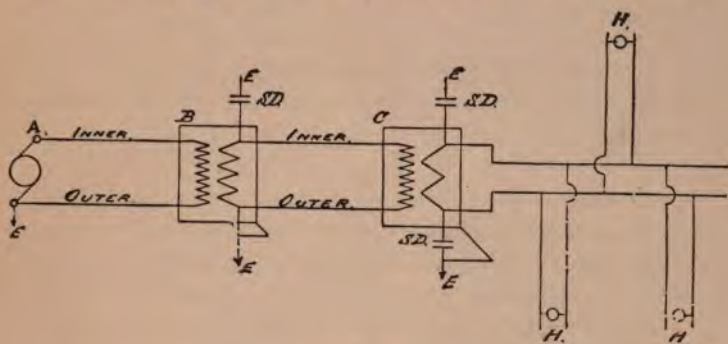

FIG. 99.

terminal, and the other at the secondary terminal of the transformer. The transformer cases are also connected to earth. The inner conductor of the 2,400 volt main, and both conductors of the low-pressure main, are connected to a safety device, such as the Cardew earthing device, which will connect the conductor to earth, should the difference of potential between them exceed a certain fixed amount, owing, say, to a breakdown of the insulation between the primary and secondary circuits of the transformer.

To protect themselves against accidents which might arise from faults in the house wiring, the engineers of this company have devised an automatic switch, which, in addition to earthing both conductors, when the

difference of potential between them and the earth becomes too high, also does so when the insulation of the house circuit falls below a fixed amount. This apparatus is shown diagramatically in Fig. 100. The primaries of two small transformers are connected in series across the house mains *a* and *b*, and the junction between them is connected to earth at E. The secondaries of these transformers are connected in series,

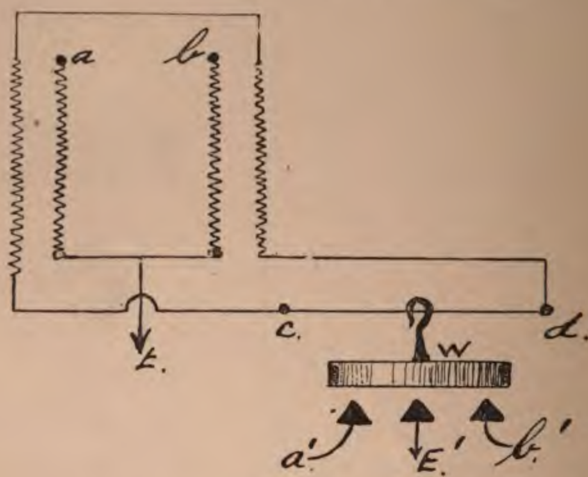

Fig. 100.

but in such a manner that they oppose one another, and are short-circuited through a fuse wire *cd*, on which a weight W is hung. So long as the pressures between *a* and earth and *b* and earth are equal, the electro-motive forces in the secondaries will be equal and opposite, and no current will flow through the fuse wire; but if the balance is disturbed by a heavy leak to earth from either *a* or *b*, or by the insulation between the primary and secondary of the 2,400 to 100

volt transformer breaking down, and raising the pressure at one terminal, a current will be produced in the secondary circuits of the safety transformers, and the fuse will be broken. This will cause the weight W to drop, and make connection between the three blocks a', b', and E′, which are connected respectively to the two sides of the house circuit and to earth; thereby short-circuiting the house mains, and causing the main fuse to blow, thus disconnecting them from the supply circuit; at the same time connecting them both to earth, so as to make it impossible for any shock to be received from a contact with them.

For the 10,000 volt current from Deptford to London, the Ferranti concentric mains, the method of making and joining which has already been described, are used. These mains, of which there are four, are carried on brackets fixed on the outside of the railway boundary wall along part of the route, and elsewhere are buried underground in troughs filled in with asphalte and tar. At intervals of 1,000 yards, or less, testing boxes are fixed. These boxes are of cast iron, with outlets at each end through which the mains are introduced, the joint between the iron tube and the outlet being made tight by caulking it with lead. The conductors are connected by clamps, which are arranged so that the contact can easily be broken, and the box is filled up with a heavy insulating oil.

The localizing of a fault in one of these mains is effected in the following manner, the apparatus used being a slide bridge galvanometer, and one or two cells capable of giving a fairly large current. At the time of smallest demand, when the load of the transformer station, whose main is faulty, can be supplied by one of the others through the 2,400 volt mains which connect the several stations together, the

inner conductor of the faulty main is looped with the inner conductor of a good main (Fig. 101), and the battery, galvanometer, and slide wire are connected up so as to form a bridge, the four points of which are A, B, C, and the fault F. The ratio of the resistances AF : FB can then be found, and from the known resistance per unit length the distance AF can be calculated, the result of the test invariably giving the correct position within 50 yards. This shows in which section of the main the fault is, and a further test is then made at the test boxes on the faulty section,

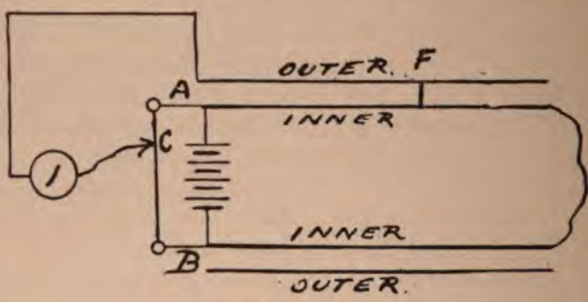

FIG. 101.

which generally gives the position within 5 yards. To remove the fault, the ground is opened up for a length of 20 yards or more, the main is sprung out into the form of a bow, thereby increasing its length, and allowing the joint to be pulled apart, and the faulty length to be replaced by a good one. If the fault occurs in such a position as to render the opening up of a long length of trench too expensive or inconvenient, the main may be cut and the length replaced, the joint being made in a box similar to that used at the testing points.

The 2,400 volt mains are concentric cables, mostly

of the lead-covered jute type armoured, but there are also some lead-covered unarmoured cables, and some vulcanized india-rubber cables, these latter being the cables which were in use underground when the generating station was at the Grosvenor Gallery, and which have been taken up and made concentric. The armoured cable is laid in a trench without further protection, and the joints are made in boxes filled up with oil; the other cables are sometimes jointed in the same way, and sometimes by making the ordinary soldered joint, and insulating it in the manner already described.

THE METROPOLITAN ELECTRIC SUPPLY COMPANY.

This company operates three stations on the alternating current transformer system, at Sardinia Street, Rathbone Place, and Manchester Square, the pressure employed being 1,000 volts. The mains consist throughout of vulcanized rubber cables, drawn into cast-iron pipes. Manholes are provided at corners, and elsewhere, as required, to facilitate the drawing in or out of the cables; and split T-pieces are inserted in place of the ordinary pipe for making connections to consumers' premises. This system of mains is probably the most perfect example of a drawing in and out system, as there are no T-joints in the cables, and the mains are laid in such a manner that individual sections can be disconnected, drawn out, and replaced, without interfering with the supply of current to any consumer. The general arrangement is shown diagrammatically in Fig. 102, where A and B are the terminals of the dynamo, and H_1, H_2, etc., the primary terminals on the consumers' premises. From A a length of cable is laid to the terminal of the primary fuse at H_1, and from H_1 another length is laid to H_2, and

so on, H_4 being connected by a cable to A. In a similar manner a complete loop of cable is run from B, calling in at each consumer's and back to B again.

The ⊤-joint, by means of which the service wire is generally connected to the main, is thus done away with, the circuit being completed by running the main cable into the house and out again. This of course necessitates the use of rather more cable; but, as the

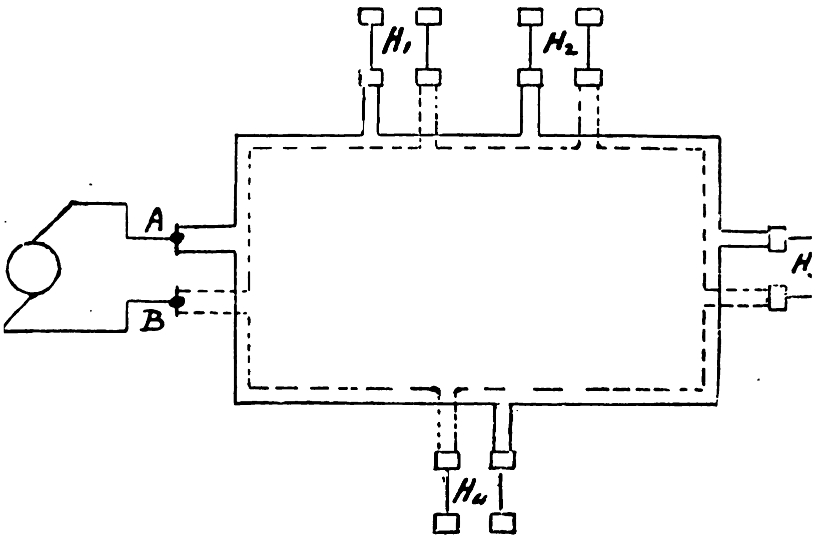

FIG. 102.

mains are generally laid under the footway, the distance from them to the primary fuse boxes, which are placed in the cellars, is very short; and the cost of the extra cable is in most cases found to be less than that of making two reliable ⊤-joints. Apart, however, from the question of cost is that of convenience, and in this respect the arrangement of mains adopted has great advantages. It will be seen that each consumer

is supplied with current by two routes, H_3 for instance being connected to the dynamo by the cable going to H_4 as well as by that which goes to H_1 and H_2; and therefore it is possible to disconnect the length of cable joining two consumers, say H_2 and H_3, without stopping the supply of current to either. This facilitates very much the localization and repair of a fault; as, supposing that the tests at the station show that there is a fault on the circuit, it is easy to find out in which section it is by disconnecting each one in turn, and testing it separately; and when the faulty section has been found, it can be drawn out of the pipe, and a fresh length of cable drawn in, whilst the remainder of the circuit is working. Again, if connections have to be made to a new customer, say between H_3 and H_4, the section joining these two is pulled out, and is replaced by two shorter sections, one from H_3 to the new premises and one from them to H_4; H_3 and H_4 receiving their supply of current in the meantime, the one by the upper cables in the diagram, and the other by the lower ones.

In addition to the distributing system from each generating station, which consists, as we have seen, of a number of loops; the three stations are connected together by trunk mains (each consisting of four pairs of rubber-covered cables in a cast-iron pipe), so that any station may be able to supply current into the distributing systems of the others; either in case of a breakdown, or when the demand for current is so small that all that is required in the three districts can be supplied by one station.

THE HOUSE TO HOUSE ELECTRIC LIGHT COMPANY.

This company, who supply current at a pressure of 2,000 volts from their station at West Brompton, have

also adopted conduits composed of cast-iron socket pipes, and into them they draw cables insulated with vulcanized india-rubber. The cast-iron pipes have holes drilled in their underside to allow water to drain off, and are laid under the road or footway, with cast-iron manholes and service boxes as required. The manholes, which are placed at all bends in the line of pipe, and also where distributing mains branch off, consist of

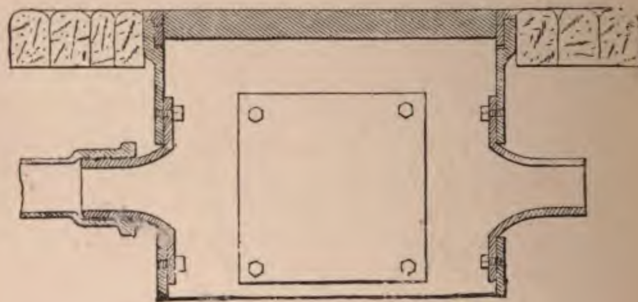

FIG. 103.

cast-iron boxes (Fig. 103) about 3 feet long by 18 inches wide, open at the bottom, and provided with a seating at the top for a cover frame. The sockets to receive the pipes are not cast with the box, but the box is made with an opening on each of the four sides, which, if not required, may be closed by a flat plate bolted in from the inside; and into which, when pipes are to be led to the box, is placed a special casting consisting of a cone-shaped socket with a large flange, which is bolted to the box. The socket is made of a diameter to suit the pipe, and, from its cone shape, offers a good surface free from sharp angles for the cables to pass over when they are being drawn in.

The service boxes (Fig. 104), which are placed opposite each alternate party wall, consist of a short piece

of pipe, enlarged somewhat in the middle, and carried up square in the upper half so as to form an oblong box, in the sides of which holes are tapped for fixing the wrought-iron gas pipes used for the service connections. These holes are closed with screw plugs when no branch is required at the box. The top of the box is finished off with a flange, and is closed by an iron lid, this lid being fixed in place by a cast-iron clamp provided with claws, which catch the under sides of the flanges and with a screw which bears on the top of the cover. These boxes are not surface boxes, but are buried below the pavement.

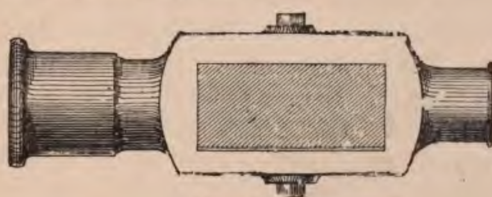

FIG. 104.

The system of mains is that which has been called the tree system, branches being taken off the main cables, and from these branches other smaller ones, until finally the house service wire is come to. Great attention has been paid by this company to the insulating of the joints, which are all vulcanized *in situ* in the manner described in chapter IX.

A similar system of laying underground mains has been employed at Hastings and Eastbourne, two of the earliest central stations in England; the conduits consisting of cast-iron socket pipes, provided with manholes and service boxes, into which the cables are drawn. At Hastings the first cables, laid down in 1883, were insulated with gutta percha and braided overall; these cables gave a good deal of trouble, and in 1884 some

rubber insulated cables were laid; and, as these proved satisfactory, the gutta percha cables, whenever a section became faulty, were replaced by rubber ones. The faults were chiefly due to mechanical injuries caused when drawing in the cable; and, as in this respect the rubber cable was much superior, very good results have been obtained with it, so much so that they have never had occasion to replace a length of it at any time. The system of distribution is a series one requiring a pressure of about 1,600 volts.

At Eastbourne, where work was commenced about the same time, rubber-covered cables have been used. At first there was some trouble with these cables, due in great measure to the fact that they were drawn into pipes of too small a size, and that they were damaged in the drawing in. Larger pipes were laid, and a more heavily insulated cable drawn into them, with much better results; and these cables have worked satisfactorily, with an alternating current at a pressure of 2,000 volts, since 1886, when this system was adopted. The rubber covering of these cables was unvulcanized, and the joints were insulated with pure rubber and then a covering of gutta percha, but latterly vulcanized rubber insulation has been used, and the joints vulcanized. The chief cause of trouble has been with the joints, and although this has been overcome, by vulcanizing them, so far as the large and medium sized cables are concerned; the results have not been so satisfactory with the small branch cables, in which it is more difficult to make a perfect joint.

Although there are now in London no stations working with overhead circuits, there are several in provincial towns, of which we may take Reading and Exeter as examples. In both these towns a series system working at about 1,500 volts is used for arc

lighting, and an alternating transformer system at 2,000 volts for incandescent lamps. At Reading the cables are insulated either with bitite or okonite, and are suspended from bearer wires in accordance with the Board of Trade regulations; whilst at Exeter the cables are insulated with india rubber, and are suspended without bearer wires from fluid insulators fixed on wrought-iron poles, the bearer wires being dispensed with on account of the shortness of the spans.

On the Continent a considerable number of stations, working on the alternating current transformer system, have been erected by Messrs. Ganz & Co.; some with overhead wires, and some with underground; the former being used in some of the smaller towns, and also for the feeders from stations placed outside the town, to the town itself; and the latter in the larger towns. The overhead wires are attached to ordinary double-bell or fluid insulators, and the underground mains are usually concentric cables insulated with jute, lead-covered, and armoured, though in some few cases rubber cables are used. In most cases transformer stations are used, from which the consumers are supplied by a low-pressure network, the best example of this being the installation at Rome. Concentric cables insulated with impregnated jute, lead-covered, and armoured, are laid in a wooden box filled with cement, and the joints are made with clamps in cast-iron boxes (Fig. 105), which are afterwards filled up with an insulating oil.

At Madrid and Barcelona, installations have been carried out on the alternating transformer system employed by the House-to-House Company, vulcanized rubber cables being drawn into iron pipes, and the joints insulated with india-rubber and vulcanized.

At Havre there is an installation on the Ferranti

system, in which underground cables are worked at a pressure of 2,400 volts. These cables are insulated with vulcanized india-rubber, lead-covered, and armoured, and are laid in the ground without further protection. The joints were originally made by clamping the conductors together, wrapping them with india-rubber strip, and enclosing the whole in a cast-iron box, which was filled up solid with bitumen. These joints, however, gave a great deal of trouble, and they have all had to be re-made; the method adopted being to make a soldered joint, insulate it with india-rubber and vulcanize it;

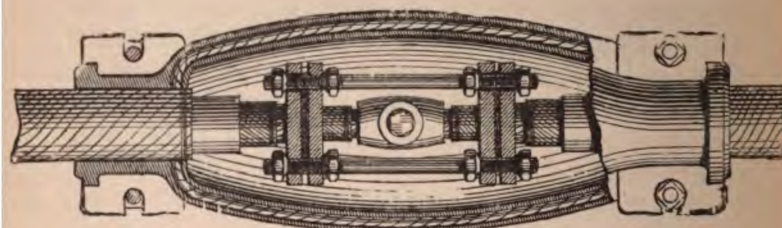

FIG. 105.

and these joints have been found very satisfactory, and are working well.

The high-pressure circuits in America, both for arc lighting in series, and for incandescent lighting by the transformer system, are more often overhead than underground; but of late years, owing to the objections raised in many of the larger towns to the use of overhead wires, a considerable mileage of underground conductors has been laid. The city of Chicago was one of the first to insist on underground work; and at the present time there are no overhead electric light circuits in the city itself, which is divided up into twelve districts, each to be supplied by a central station

as near the centre as possible. The plan of distribution is to build a main subway extending right across the district, with branches running out at right angles, and reaching to the other boundary lines. Various conduits are used; iron pipes laid in the ground or in concrete, cement-lined iron pipes in concrete, and the Dorsett conduit, all being employed; into these conduits are drawn cables, either insulated with rubber mixtures such as kerite, okonite or vulcanite, or with fibrous material enclosed in a lead tube. The conduits are provided with rectangular brick manholes placed from 80 to 150 yards apart. The Chicago Arc Light and Power Company operates over 2,000 arc lamps by means of underground cables, some of which are Patterson cables, insulated with fibrous material impregnated with paraffin to a thickness of $\frac{3}{16}$ths of an inch, and drawn into a lead pipe; and some, Norwich cables insulated with paper to a thickness of $\frac{5}{32}$nds of an inch, and lead covered. The joints, which have been the chief cause of trouble, more especially with the paraffin cable, from which it has been found difficult to exclude moisture, are made by soldering the two ends of the conductors into a copper sleeve, covering the joint with insulating material, and moulding over it a solder connection from lead to lead. A large portion of their conduit is of the Dorsett type; but they also use $2\frac{1}{2}$ inch wrought-iron pipes, and a conduit made of pine logs $4\frac{1}{2}$ inches square outside, and bored lengthwise with a circular hole $2\frac{1}{2}$ inches diameter (see Figs. 81, 82). This latter conduit has been in use for two years, and has so far given satisfaction; and it further has the advantage of being cheap. The average pressure on these arc lighting circuits is 2,500 volts. Besides the underground circuits in the city itself, this company has some 80 miles of overhead circuits, outside the city boundary,

which are used for arc lighting, the pressure in some cases reaching as high as 4,000 volts. The overhead wire is covered with a triple braiding, is supported on glass insulators attached to the pole arms, and is protected by lightning arresters of the Thomson-Houston type fixed at both ends of each circuit in the station.

The Westinghouse Company, who have done a very large share of the work in connection with incandescent lighting on the alternating current transformer system, as well as arc lighting in series with both continuous and alternating currents, use for the most part overhead wires; some of which, on arc light circuits, carry current at a pressure as high as 5,000 volts. The cables are supported without bearer wires on insulators attached to the pole arms, the spans being arranged in such a manner that there is practically no danger of the conductor breaking. All the circuits are protected by their special types of lightning arrester, of which descriptions were given in chapter XIII. The highest pressure employed on any of their incandescent lamp circuits is 4,000 volts, at Portland, Oregon; where they have a plant working with a double transformation. The generating machinery is driven by water power at a station situated 12 miles from the city, and supplies current at 4,000 volts to sub-stations in the city, where it is reduced to 1,000 volts; at which pressure it is distributed to the transformers on the consumers' premises, and there it is further reduced to 50 volts. The maximum pressure usually employed on the incandescent circuits is 1,000 volts.

When underground cables are used, they are always lead-covered, and are of one of three types, viz.: the Standard cable, insulated with fibrous material impregnated with compound; a cable insulated with soft rubber; or a cable insulated with vulcanized

rubber, the rubber being separated from the lead by a layer of paraffin. In some cases, especially for feeders, a duplex cable is used, in which the two insulated conductors are enclosed in the same lead casing. These cables are drawn into iron pipes, or cement-lined sheet-iron tubes, laid in cement and provided with manholes for giving access to the cables. Joints are made by soldering the conductors into a metal sleeve, wrapping them with tapes or rubber strips, and covering the entire joint with a lead sleeve wiped on to the lead armouring with a plumber's joint. All these types of cable are working well, the chief cause of trouble, when there is any, being the failure of a joint; but when this occurs it is usually detected by the insulation tests before it causes any interruption of the service.

The Thomson-Houston Company's system of distribution, whether for arc lamps in series, or for incandescent lighting by alternating current transformers, is mostly carried out by means of overhead wires, continuously insulated and supported on glass insulators on the pole arms. The transformer circuits are usually supplied with a primary pressure of 1,000 volts, which is reduced in the secondary circuit to 52 or 104 volts. The circuits are protected by lightning arresters in the station, and are generally arranged so that feeders are run to various points, which form centres of distribution, and at which fusible cut-out boxes are fixed on the poles. From these cut-out boxes are branched off the distribuing mains, which are of such a section that the loss of pressure is only about one half per cent. To these mains, just before they arrive at the transformer, is connected a lightning arrester; and on the secondary side of the transformers is fixed a safety device, which has been designed by the company to

protect any person, touching the secondary conductors, from the possibility of a shock, due to the introduction in the circuit of a higher pressure than the normal working one. This apparatus consists of three insulated terminal blocks, the central one of which is connected to earth, whilst the outer ones are connected to the secondary conductors. A flat brass spring is attached to the middle block, in such a manner that each end of it is pressed up against one of the outer blocks; from which, however, it is separated by a thin paper film, prepared so that it will withstand the strain due to the ordinary working pressure, but will be pierced as soon as the pressure between the secondary terminal and earth reaches a previously determined value. If the insulation of the circuit is faulty so that a shock would result from contact, the connection to earth, which is made as soon as the paper is pierced, short circuits the secondary and causes the primary fuse to blow, thus cutting the transformer out of circuit.

CHAPTER XVI.

Testing Cables during Laying and Jointing.—Testing Completed Installations.—Difficulties with Single Wire and Concentric Systems.—Testing Installations when Working.—Lamp Test.—Voltmeter Test.—Bridge Test with Working Current.—Lamp and Voltmeter Tests on High Pressure Alternating Circuits.—Vacuum Tube Indicator.—Localizing Faults.—Use of the Telephone.—Dividing Mains into Short Sections.

THE importance of a complete system of testing cables before they leave the factory, has already been referred to; and we have now to deal with an equally important subject, namely the testing of the cables after delivery, and of the complete installation after it has started working. This is a matter which is too often neglected, with the result that a small fault, which might easily be repaired, is allowed to develop into such a serious one that it interferes with the working of the circuit, and causes a breakdown. When we consider the chances that occur of injuring the cables, mechanically or otherwise, during the laying of underground mains, or the erecting of cables overhead, or in buildings, it must be evident that continual testing is necessary, if we are to make certain that the work is done properly; and, as it is much easier to trace a fault immediately it has been caused, and when it is pretty well known what section of the work it is in, than it is when there is no guide as to its whereabouts, it is important that tests should be made regularly as the work proceeds. For instance, suppose that a system of underground mains is being laid, the work is done in sections, and the several sections are afterwards jointed

together. Now, if each section, as it is laid, is tested, and if a test is made on the mains, before and after the joints are made which connect on to the system another section of cable, any fault which has been caused in laying can generally be traced pretty easily; whereas if half a dozen sections are joined together before a test is made, it becomes very difficult to localize a fault; indeed it is probable that, before this can be done, the joints which have just been made may have to be unmade, and the several sections separated again. The most important test is of course that which measures the insulation resistance of the cables; and as a fault may occur either through a leakage from one conductor to the other, or through a leakage from either conductor to the earth, there are three resistances that have to be determined.

During the laying and jointing of the cables, the insulation tests may be made in the manner described in chapter XI., either with a reflecting galvanometer and other apparatus as used in the factory, or when this cannot be done, with some form of portable testing apparatus. The former apparatus may, and should always be fitted up in the test room of every central station; whilst for outdoor work, or for testing the insulation of installations in buildings and ships, a portable testing set should be provided. This latter apparatus may be obtained in various forms, a convenient one being a small box containing a sensitive galvanometer provided with two or three shunts, a standard resistance for taking the constant, and the necessary terminals and keys. With this test box there should be provided a battery of small testing cells, fitted in a separate box, in number sufficient at the least to give a pressure of about 50 volts, though preferably the pressure should be higher. Another form of portable

apparatus, which is frequently used, consists of an ohmmeter suitable for measuring high resistances, and a magneto machine, which should be capable of giving a pressure of about 200 volts.

When the installation is completed, and the lamps and other receiving apparatus connected up, it is no longer possible to measure directly the insulation resistance between the two conductors; since the conducting bridge formed by the lamps has a much lower resistance than that of the leakage circuit, and any measurement therefore would give practically the resistance of the lamps, and not the insulation of the cables. The insulation of the circuit from earth can however always be measured, except in the particular case in which one conductor is permanently connected to earth, as in the single-wire system; and, if the mains are laid in such a manner that no current can leak from one conductor to the other, without the earth forming part of the leakage circuit, we can always tell that the insulation between the two conductors is higher than that between the conductors and earth; because, in the latter case, the insulation resistances of the two conductors are connected in parallel, whilst, in the former, they are in series with one another.

Herein lies one great advantage of a double-wire system, when arranged in such a manner that each cable is surrounded by a good conductor connected to earth; as, for instance, when the cables are in water, or are armoured, or when each cable is enclosed in a metal pipe, the pipe and armouring being earthed; since, under such conditions, any leakage must in the first instance be from a conductor to earth. On the other hand, if a single-wire system is employed, there is no way of ascertaining the state of the insulation, unless all the lamps are disconnected; and the same

holds good with any system of concentric wiring, since the state of affairs then is that there can be no leakage to earth from the inner conductor, unless the outer conductor forms part of the circuit. Of course, if the double-wire system is arranged so that no conductor connected to earth is interposed between the two cables, as when they are both laid together in a semi-insulating conduit, or even when they are laid in separate grooves in wood casing, it is quite possible that the insulation resistance from one conductor to the other may be lower than that between the two conductors and earth.

With this method of fixing the cables, or with a concentric cable, there is a smaller chance of any person receiving a shock, if the insulation afforded by the conduit is high, or the concentric system is carried out thoroughly; but, in the majority of installations, this is a matter of less importance than the prevention of leakage from one conductor to the other, as this fault may be the cause of a fire, or of an interruption of the service. A further advantage resulting from the use of a system of wiring in which any fault must of necessity be, in the first instance, an earth fault, is that a continuous test may be kept on the insulation whilst the circuit is working; and therefore any falling off in insulation can be known as soon as it occurs; and, as the connection of one conductor to the earth need not interfere with the working of the circuit, there is generally an opportunity of localizing and repairing the fault, before it develops into a short circuit, or in any way necessitates the cutting off of the current.

After an installation has been started, it may happen that there is no opportunity of measuring the insulation resistance by the methods already referred to,

because the working current is on continuously; and other methods, in which the working current itself is used for testing, must then be employed. Even if it is possible to test the circuit when the current is off, a test with the working current is more satisfactory, because it is made under the actual working conditions; and it sometimes happens that a fault may exist then, although the circuit may test well when the current is cut off. For instance, if the working pressure is much higher than that which can be used in conjunction with the testing apparatus, the current may spark across an air gap, or leak over a surface across which the testing current, owing to the smaller strain set up by it, may be unable to pass. Again, it may happen that the expansion of some part of the conducting circuit, due to the higher temperature when the current is on, may cause a fault which disappears again as soon as the temperature falls. The tests which can be made with the working current are not, as a rule, such as will give very accurate quantitative results, and therefore it is advisable to employ both methods; that is to say, an apparatus should be permanently connected in the circuit, which will at all times show whether the insulation is above or below the safe minimum; and at intervals, as an opportunity occurs, the resistance of the cables should be measured by the galvanometer method, so as so obtain a record of the behaviour of the cables themselves.

One method, very commonly employed on low-pressure direct current circuits, is to connect a lamp or lamps to the conductors and to the earth, in such a manner that one will glow when there is a leak of sufficiently low resistance on the circuit. Sometimes two lamps are connected in series between the conductors, and the junction between the two lamps is connected to earth.

If the insulation resistance of the positive conductor is much lower than that of the negative conductor, the lamp connected to the latter will glow more brightly than the other one; and any change in the brightness of the lamps will therefore indicate a change in the relative values of the insulation resistances. If, however, the insulation of both conductors is equally low, the lamps will both glow to the same extent, just as they would if the insulation was good in both cases; and therefore this method is not of much use, except as a handy detector for faults of very low resistance, which seldom occur at the same moment on both sides of the circuit. Another way of employing a lamp as a detector is to connect it up with one terminal to earth, and the other to a two-way switch, by means of which it can be connected first to one, and then to the other conductor. In this case, if the lamp is connected, say, to the positive conductor, it will glow when the added resistances of itself and of the insulation of the negative conductor are small enough to allow sufficient current to pass. In both cases, the resistance of the lamp should be as high, and the current required to make it visibly hot as low, as possible; so that an indication may be given of faults which have some appreciable resistance. Of course on low-pressure circuits it is not only the resistance of the mains, but also that of all the installations connected to them, that is measured; and therefore, when a large number of lamps are supplied from a station, one does not have very high resistances to deal with, and one is content so long as nothing in the shape of a dead earth occurs;—that is to say, a leak, of sufficient magnitude to light two or three lamps when connected in parallel between one conductor and the earth, is in some cases required, before it is considered necessary

to start out on a fault-finding expedition. When this is the case, the simplicity of the lamp method is much in its favour, as the test can be made at any time by the station attendants, who can note when the lamp glows brightly, and report to the electrician accordingly.

If voltmeters are substituted for the lamps in the first case, an approximate measurement of the ratio of the two insulations can be made. It has sometimes been stated that the resistances are proportional to the readings of the voltmeters, but this is only true when the resistance of the voltmeter is infinitely great compared with that of the fault; since otherwise, the resistance of the voltmeter, being in parallel with that of the fault, materially alters the proportions of the resistances between the conductors and earth. This method is however used by some companies, as, for instance, the Liverpool Electric Supply Company, who employ recording voltmeters, and when any great difference in their readings is indicated, measure the leakage current by momentarily connecting a low-resistance ammeter between earth and the conductor of higher insulation resistance.

Actual measurements of the insulation resistance can be made with a voltmeter of known high resistance, if three readings are taken; one of the pressure V between the two conductors, one of the pressure V_1 between the positive conductor and earth, and one of the pressure V_2 between the negative conductor and earth. If the resistance of the voltmeter is R, and the insulation resistances of the positive and negative conductors R_1 and R_2 respectively, we obtain the following relations :—

When the voltmeter is a shunt on R_1 their joint resistance is $\frac{RR_1}{R+R_1}$, and the total resistance between

the conductors is $\frac{RR_1}{R+R_1}+R_2=\frac{RR_1+RR_2+R_1R_2}{R+R_1}$.

Since the difference of potential between any two points in a circuit, in which a current is flowing, is proportional to the resistance between those points,

$\frac{V}{V_1}=\frac{RR_1+RR_2+R_1R_2}{RR_1}=1+R_2\frac{R+R_1}{RR_1}$. This gives

$R_2=\frac{(V-V_1)RR_1}{V_1(R+R_1)}$. Similarly when the voltmeter is connected to the negative conductor, $\frac{V}{V_2}=\frac{RR_1+RR_2+R_1R_2}{RR_2}$,

which may also be written $\frac{V-V_2}{R_1V_2}-\frac{1}{R}=\frac{1}{R_2}$. Substituting the value of R_2 given above, and bringing all the terms containing R_1 to one side, we get

$$R_1\left(\frac{V}{V-V_1}\right)=R\left\{\frac{V^2-VV_1-VV_2}{V_2(V-V_1)}\right\},$$ and dividing

both sides by $\frac{V}{V-V_1}$ gives $R_1=R\frac{V-V_1-V_2}{V_2}$.

Since $\frac{V_1}{V_2}=\frac{R_1}{R_2}$, we also get $R_2=R\frac{V-V_1-V_2}{V_1}$.

This test should be made with a voltmeter having a high resistance, if it is desired to measure the insulation of a circuit in fair working order; as with the ordinary range of calibration, it is not possible by this test to measure a resistance of more than ten times that of the voltmeter.

Another method, by means of which resistances can be measured over a great range, is one in which the dynamo is used to supply current to a Wheatstone bridge, two arms of which are formed of the two insulation resistances, whilst the other two consist of a known fixed resistance and an adjustable resistance. In addition to these resistances, a second resistance

coil of known value is required. The connections for this test are shown in Fig. 106, in which + and − are the two main conductors, R_1 and R_2 are the insulation resistances of the two conductors from the earth E, R is the known fixed resistance, r the adjustable resistance, and G the galvanometer. To make the test, r is first adjusted until there is no deflection of the galvanometer, when $\frac{R_1}{R_2} = \frac{r}{R}$; then the second resistance coil ρ is connected as a shunt on R_1, and a fresh balance is

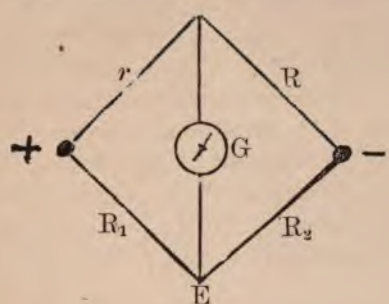

FIG 106.

obtained say with r_1 ohms in the adjustable resistance, when $\dfrac{\frac{R_1\rho}{R_1+\rho}}{R_2} = \frac{r_1}{R}$. From these two equations the value of R_1 can be obtained, by substituting in the second equation for R_2 its value in terms of R_1.

Thus $\dfrac{\frac{R_1\rho}{R_1+\rho}}{\frac{RR_1}{r}} = \frac{r_1}{R}$, and simplifying this, gives $R_1 = \frac{\rho(r-r_1)}{r_1}$.

R_2 can then be found from the equation $R_2 = \frac{RR_1}{r}$.

The methods which have just been described are

only applicable to circuits working with a moderate pressure, and have to be modified somewhat before they can be used on high-pressure alternating circuits. The lamp method may be used with a transformer, the primary circuit of which is connected to one conductor and to earth, whilst a lamp is connected to the secondary circuit; but since it will only indicate the existence of faults of low resistance, it is not very satisfactory for use on high-pressure circuits, where it is important that the insulation should be high, both because the waste due to a leakage of current is relatively much more important than on a low-pressure circuit, and also because the danger arising from contact with a conductor is greater. A Cardew voltmeter in series with a non-inductive resistance of from 5,000 to 10,000 ohms may be used; or each conductor in turn may be connected to earth through such a resistance, and the difference of potential between the conductor and earth measured by an electrostatic voltmeter.

An altogether different plan is adopted by the House-to-House Company, in which the glow in a vacuum tube is used as the indicator. A vacuum tube, placed inside a darkened box, is connected up between the earth and the conductor under test; if the insulation is high there is a visible glow due to the discharge through the tube; but, as the insulation resistance becomes less, this glow diminishes in brightness, thus giving an indication of the condition of the mains.

When by one or other of these methods the existence of a fault has been detected, the next operation is to localize it, so that it may be repaired; and this is often a very troublesome matter. When one tests for a fault by the loop test, it is necessary to know the conductor resistance of each part of the circuit, so that,

from the ratio of two resistances, the length of cable between the testing station and the fault may be calculated.

Although this is a simple matter, when a length of cable is being tested in the factory, the conditions are altogether different when we have to deal with a network of conductors off which branches are taken, and to which lamps, transformers, or other apparatus are connected. There are a few special cases in which a fault of moderate resistance can be localized by the loop test; as, for example, in feeding mains which can be entirely disconnected from the rest of the circuit; but, as a general rule, such tests cannot be applied to electric light circuits, owing to the uncertainty which

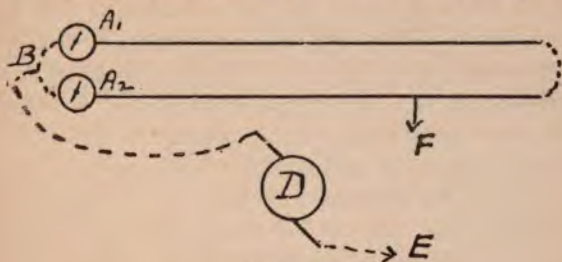

FIG. 107.

must always exist as to the value of the conductor resistance in a network of cables with branches taken off at various points. When the conditions are favourable, the following method has been proposed as an alternative to the tests described in chapter XI.:—

Connect the distant ends of the two cables together, and join up the two ends in the station with an ammeter included in the circuit of each conductor. Connect one terminal of a dynamo, or battery of accumulators, to the common junction of the cables in the station, and the other terminal to earth (Fig. 107).

It is evident that, as the two circuits, BA_1F and BA_2F, are connected in parallel, the currents C_1 and C_2, through A_1 and A_2, will be inversely proportional to the resistances of the two circuits; and that, if we denote the total length of the loop by l, and the distance BA_2F by x, then $\frac{C_1}{C_2} = \frac{x}{l-x}$, or $x = l\,\frac{C_1}{C_1+C_2}$.

When instrument testing fails, a trolly carrying an iron plate, on which is wound a coil of wire connected to a telephone, is sometimes used; the plan adopted being to wheel it along the route of the mains, whilst an alternating or pulsating current is sent through the cable to earth. As the trolly is wheeled along, the person testing listens at the telephone, and can tell when the fault is passed by the cessation of the sound emitted by it. The idea is a very ingenious one, and the apparatus has been used with considerable success in various places; but there appears to be a risk of discovering imaginary faults, owing to the presence of other disturbing influences; and in one or two cases where this system has been tried, considerable trouble has been caused by the apparent localization of a fault where actually none existed.

Notwithstanding the immense importance of this matter, we are obliged to confess that, up to the present time, no really reliable methods have been introduced, which will enable us to fix the position of a fault with anything approaching accuracy, under the conditions which usually exist; and a careful consideration of the subject leads one to the conclusion that the only satisfactory way of laying mains, so that faults can be readily localized and repaired, is to divide them up into a number of short sections, each of which can be entirely disconnected from all others, and from all house connections; so that each individual section can

be tested separately, and if found to be faulty can be drawn out from the pipe or conduit, and be repaired or replaced by a good length of cable. If, at the same time, the mains are arranged in such a manner that there are alternative routes from the station to each consumer's premises, and the sections into which they are divided are short, the testing and repairing of them can be effected with the minimum of inconvenience to the users of the current; and it will therefore be generally found worth while, even if it increases the first cost of the mains, to lay them on such a system, owing to the very considerable advantages which may be gained as regards facilities of testing and repairs.

INDEX.

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